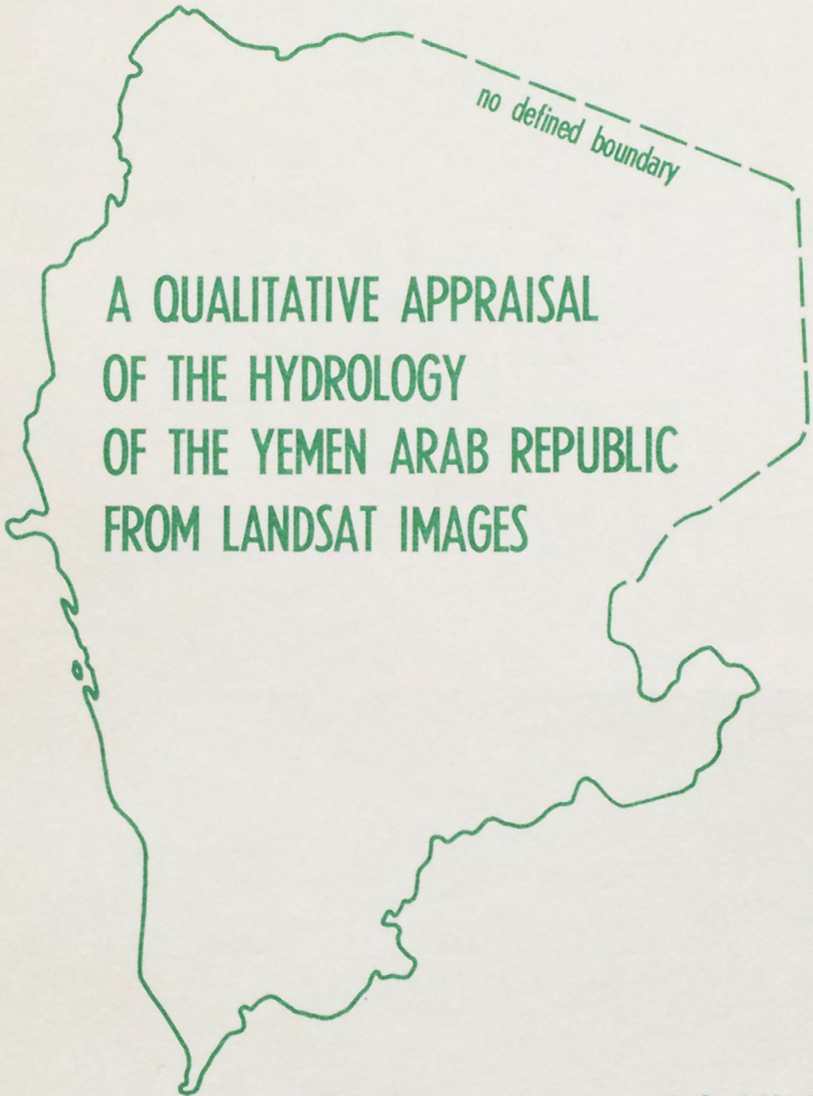
A QUALITATIVE APPRAISAL OF THE HYDROLOGY OF THE YEMEN ARAB REPUBLIC FROM LANDSAT IMAGES



U.S. GEOLOGICAL SURVEY

Open-File Report 80-565

Prepared in cooperation with the Yemen Arab Republic under the auspices of the United States Agency for International Development

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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By Maurice J. Grolier, G. C. Tibbitts, Jr.,
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Reston, Virginia
1981

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, *Secretary*

GEOLOGICAL SURVEY

Doyle G. Frederick, *Acting Director*

For additional information write to:

Chief, Office of International Hydrology
U.S. Geological Survey
470 National Center
Reston, VA 22092

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A QUALITATIVE APPRAISAL OF THE HYDROLOGY OF

THE YEMEN ARAB REPUBLIC

FROM LANDSAT IMAGES

By Maurice J. Grolier[1], G. C. Tibbitts, Jr.[2], and

Mohammed Mukred Ibrahim[3]

ABSTRACT

Landsat-1 and Landsat-2 images were analyzed in June 1976 to describe the flow regimens of streams and the regional distribution of vegetation in the Yemen Arab Republic (YAR). The findings provide a factual basis for planning a surface-water data collection program, and for preparing maps of plant distribution and agricultural land use. They lay the foundation for modernized water development, and for effecting a program of country-wide water management in the YAR. The work was undertaken as part of the program of the U.S. Agency for International Development with the cooperation of the Mineral and Petroleum Authority, Ministry of Economy, YAR.

Nine Landsat scenes cover the entire YAR. A false-color composite mosaic of nine corresponding images was prepared using Landsat-1 images taken at a relatively low sun-angle in the winter of 1972-1973. Catchment

[1] U.S. Geological Survey, Reston, Virginia, USA

[2] U.S. Geological Survey, Sana (Sanʿāʾ), Yemen Arab Republic

[3] Mineral and Petroleum Authority, Ministry of Economy, Sana (Ṣanʿāʾ), Yemen Arab Republic

areas and the major drainage basins of the country were delineated on this mosaic. Additional Landsat-1 images taken in fall 1972, spring 1973, and fall 1973, and also Landsat-2 images taken in spring 1975, fall 1975, and spring 1976 provide repetitive coverage of these nine scenes. A hydrological and ecological analysis of this array of imagery shows many kinds of streamflow regimens, and along the reaches of some streams at least, yearly and seasonal fluctuations or changes in streamflow. Similar fluctuations in soil moisture and possibly in groundwater supply were inferred from variations in the size of vegetated areas, and the apparent (spectral) vigor of plant growth.

In order of increasing water availability, the four catchment areas of the YAR are: Rubʿal Khali (Ar Rabʿal Khālī), Wādī Jawf (Arabian Sea), Red Sea, and Gulf of Aden. Most streams are ephemeral. No lakes were detected during the period under investigation, but sebkhas -- salt flats or low salt-encrusted plains--are common along the Red Sea coast. In spite of the 80-meter resolution of Landsat images and the additional constraint of carrying out this hydrologic analysis at the 1:1,000,000 scale, streamflow was interpreted as perennial or intermittent, wherever it could be detected on several Landsat images covering the same scene at seasonal or yearly intervals. Much of the land under cultivation is restricted to valley floors, and to valley slopes and irrigated terraces adjacent to stream channels. Little or no vegetation could be detected over large regions of the YAR.

The relatively advanced state of water development, as evidenced by irrigation from wells or by diversion of streamflow into irrigation canals, already warrants a quantitative evaluation of water resources and land under cultivation in some parts of the Tihāmah (the coastal plain inland from the Red Sea coast) and in some of the interior valleys. Computer enhancement and photographic enlargement of perennial and intermittent streams and of the farming areas observed on available Landsat images, and large-scale thematic mapping of surface water and vegetation by band-ratioing performed on computers will constitute a first step toward an effective country-wide management of water resources and agricultural production. Systematic mapping of regional fractures, especially of intersecting fractures, on Landsat images may lead to the discovery of new sources of ground water.

Additional remote-sensing programs also should be considered, including a thermal infra-red aerial survey to detect possible ground-water discharge offshore which may be reflected in small temperature differences between Red Sea water and fresh ground water. Such an aerial infra-red survey should be undertaken with the objective of locating presently untapped ground water and intercepting it by drilling wells at critical locations on the coastal plain of the Red Sea. It should be supported on the ground by a survey of existing wells in the Tihāmah, and a water sampling program aimed at determining the chemical quality of ground water. A country-wide thermal infra-red survey would allow the systematic mapping of thermal springs, which traditionally have played an important part in the cultural life of the Yemenis, and also might help locate hot spots related to volcanism. Some hot spots might warrant further exploration in the search for geothermal energy. More advanced remote-sensing techniques such as those for estimating moisture content through the dielectric constant of materials should not be considered, however, until radar imagery has become widely available in the YAR.

INTRODUCTION

Program Objectives and Scope of the Report

Agriculture in the Yemen Arab Republic (YAR) is critically dependent on irrigation from ground water or diverted stream- and sheet-flow. In addition, the water supply of cities and individual farming commumities is everywhere dependent on water pumped from wells, water from springs, or rain collected in cisterns during torrential showers. Further development of ground- and surface-water resources is a key element in developing agricultural resources in the YAR.

The qualitative appraisal of surface- and ground-water resources contained in this report is a service rendered by the U.S. Geological Survey (USGS) under Participating Agency Service Agreement (PASA) ASIA (IC) Yem-925-22-74 between the Agency for International Development (USAID), U.S. Department of State and the USGS in cooperation with the Central Planning Organization (CPO), the Ministry of Agriculture, and the Minerals and Petroleum Authority (MPA), Ministry of Economy, YAR. The results of two segments of a Water and Minerals Survey of the YAR, called for in the PASA, namely (a) a ground-water survey of YAR north of 15 N. latitude, and (b) an ERTS (Landsat) satellite survey of the country are presented in the report. The Water and Minerals Survey of YAR is a sub-project of the Pre-Development Studies Project of USAID and YAR.

One of the goals of the sub-project has been to produce mosaics of Landsat scenes covering YAR: An improved version of such a mosaic has been prepared by the USGS, and early versions were delivered to the USAID mission to YAR in[1] Sana (Ṣanʿā') in 1975 and 1976. A geochemical report (Overstreet and others, 1976) has been released to the open file of the USGS, the CPO and the MPA in February 1976, in partial fulfillment of the third segment of the sub-project entitled "A minerals survey north of 15 N. latitude." A preliminary geologic map of YAR at the 1:500,000 scale in nine separate sheets (Grolier and Overstreet, 1976) has also been released in partial fulfillment of the second segment of the sub-project. The intent in compiling the geologic map was to bring together, at a convenient working scale, previously known geologic information and recently acquired data from Landsat scenes.

The objectives of the appraisal of the hydrology of YAR are (1) to provide sufficient data for planning the development of water resources in some areas, (2) to make recommendations to the Government of YAR as to projects and programs for evaluating the water resources of YAR, and (3) to assist YAR in the development of plans and priorities for several studies of ground-water resources (PASA 22-74).

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1 Geographic names in this report have been verified in the United States Board on Geographic Names (BGN) Official Standard Names Gazaeteer, Yemen Arab Republic, 1976, as approved by the Board on Geographic Names, Geographic Names Division, Defense Mapping Agency, Hydrologic/Topographic Center, Washington, D.C. 20315. Other processing of names, compilation, review, editing, for cartographic and report use was done in the Office of International Hydrology, National Center, Reston, Virginia 22092. See Appendix III, p. 105.

Spellings of standard names in the report are approved by BGN. Names preceded by an asterisk (*) are not approved by BGN. Previous reports used a transliteration of the native name, that is, Al Mukhā, Sanʿā', and Ar Rabʿ al Khālī, in preference to the conventional name spelling approved by BGN. In this report, the conventional name is used, followed by the native name shown in parenthesis, for example, Mocha (Al Mukhā), Sana (Ṣanʿā') and Rubʿ al Khali (Ar Rabʿ al Khālī).

In this report, the spectral reflectances of surface water, wet or moist land, and vegetation, taken at successive times, are used to identify and locate surface water and to draw inferences concerning the occurrence of ground water at shallow depth. It was not considered practical to describe the occurrence of ground water alone, as called for originally in the PASA, and the hydrogeological survey was expanded to include surface-waeer resources within the entire country, inasmuch as the Landsat survey covered the whole of YAR.

On the one hand, the presence of ground water in the YAR can be inferred from the regional distribution of vegetation, as described in this report. On the other, any discussion of ground-water systems in the YAR, beyond such generalizations as alluvium, sandstone and some lava flows being good aquifers, and granitic and metamorphic rocks being poor ones because of lower porosity and permeability, is excluded from this report by the lack of available data.

Likewise, evaluating the status of ground-water and surface-water exploration and development in the YAR, presupposes an effective, systematic, country-wide collection of hydrologic data, and a repository such as a library where these data and pertinent reports by government agencies and consulting firms are maintained for safekeeping and analysis. Our efforts to procure such data and reports, when this report was being compiled, proved unsuccessful. However, ground-water development in the YAR has a long history, spanning several thousand years. Water wells have been dug by the thousands since time immemorial in valley and coastal plain alluvium, and many are known to have been excavated by hand out of hard rock. In the last 20 years, many modern wells have been drilled and equipped with pumps under foreign aid programs of many countries, including that of USAID. Well drilling by private enterprise has been very successful in the south-central part of the Tihāmah, so much so that indiscriminate ground-water withdrawal has resulted locally, at least, in over-development. Major river basins, such as those of Wādī Mawr and Wādī Zabid are in the planning or early stages of development, but clearly, the long history of water exploration and development in the YAR, and the many accomplishments of the last 20 years are beyond the scope of this report.

The scope of this analysis is country-wide rather than regional or site-specific, as most previous hydrological investigations in YAR have been, and thus the survey is a reconnaissance, rather than a detailed study of the water resources of YAR. Nonetheless, on the strength of its results, several recommendations are made for future surface-water surveys and hydrogeological investigations.

Topography

Then YAR occupies an area of about 200,000 square kilometers (km^2) in the southwestern part of the Arabian Peninsula. On the north and northeast, the country borders the Kingdom of Saudi Arabia, on the southeast and south, the People's Democratic Republic of Yemen, and on the west, the Red Sea. Its sea coast, from the mouth of Wādī Maydī on the north to the strait of Bab el Mandeb in the south, is about 460 kilometers (km) long. The capital, Sana (Ṣanʿā), is in the north-central part of the Yemen highlands. The major cities of the country: Bājil, Al Ḥudayday (Ḥudaydah), Zabīd, Ḥays (Ḥais) on the west, Maʿbar, Dhamār, Yarīm Ib, and Taʿizz on the south, and ʿAmrān (ʿUmrām) and Al Ḥarf on the north are linked to the capital by a paved highway (fig. 1.) Gravel roads permit travel to most places in the YAR, but in the extreme eastern part of the country, these roads yield to desert tracks in Ramlat as Sabʿatayn.

The YAR has a total relief of more than 3,000 meters (m) and may be divided into five major regions (fig. 2). From west to east, these are (1) the coastal plain, plain, called at Tihama (or simply, the Tihāmah (Tihama), which borders the Red Sea; (2) a west-facing mountainous escarpment (Red Sea escarpment); (3) the Yemen Highlands; (4) Wādī Jawf valley; and (5) the southwestern fringe of Rubʿ al Khali (Ar Rabʿ al Khālī). The firts three regions extend from north to south and are parallel to the Red Sea coast. Wādī Jawf valley trends southeastward toward Ramlat as Sabʿtayn, a sandy

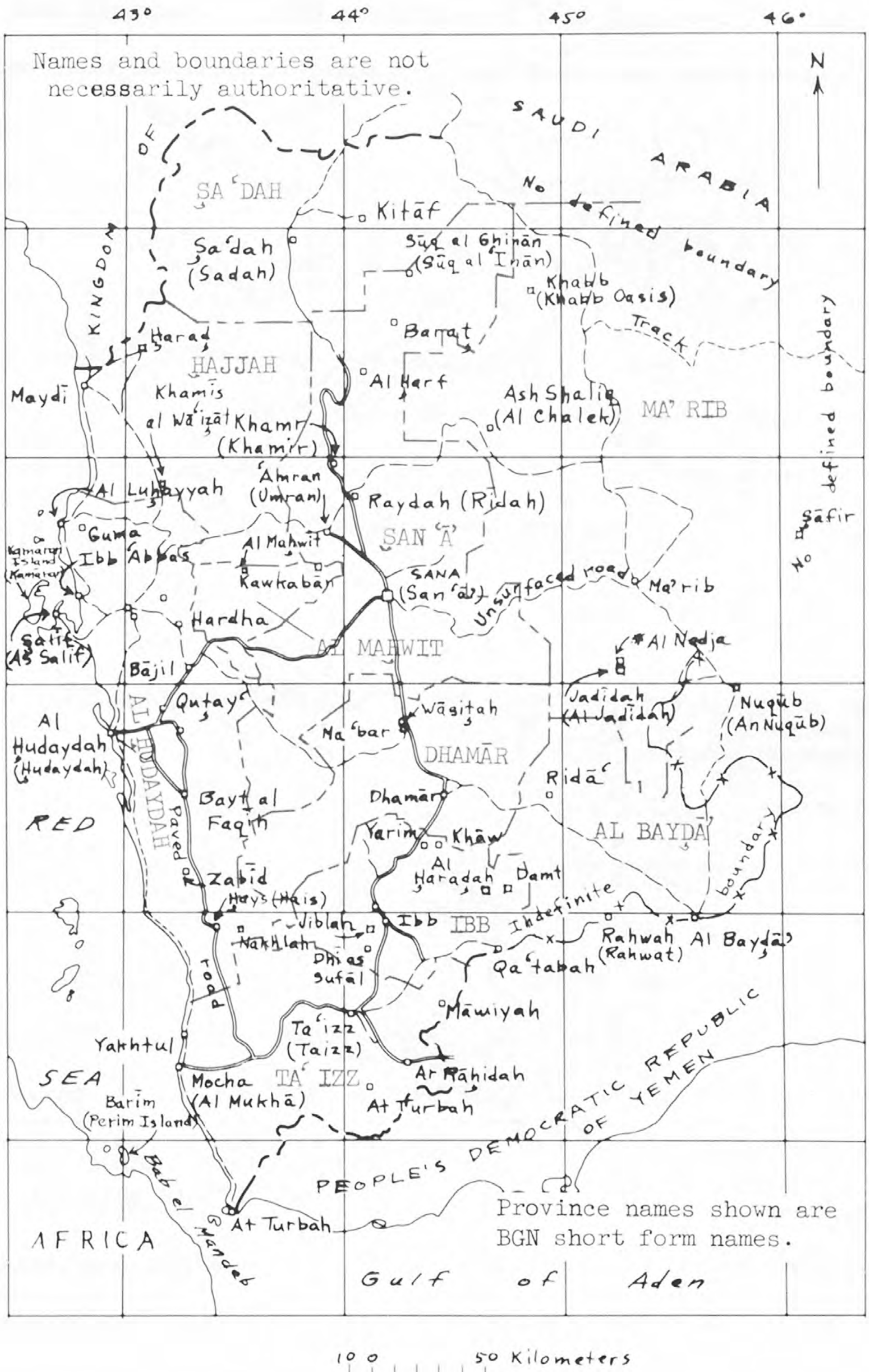

Figure 1--Index map of the Yemen Arab Republic (YAR) and the network of highways and major roads, with other roads and car tracks.

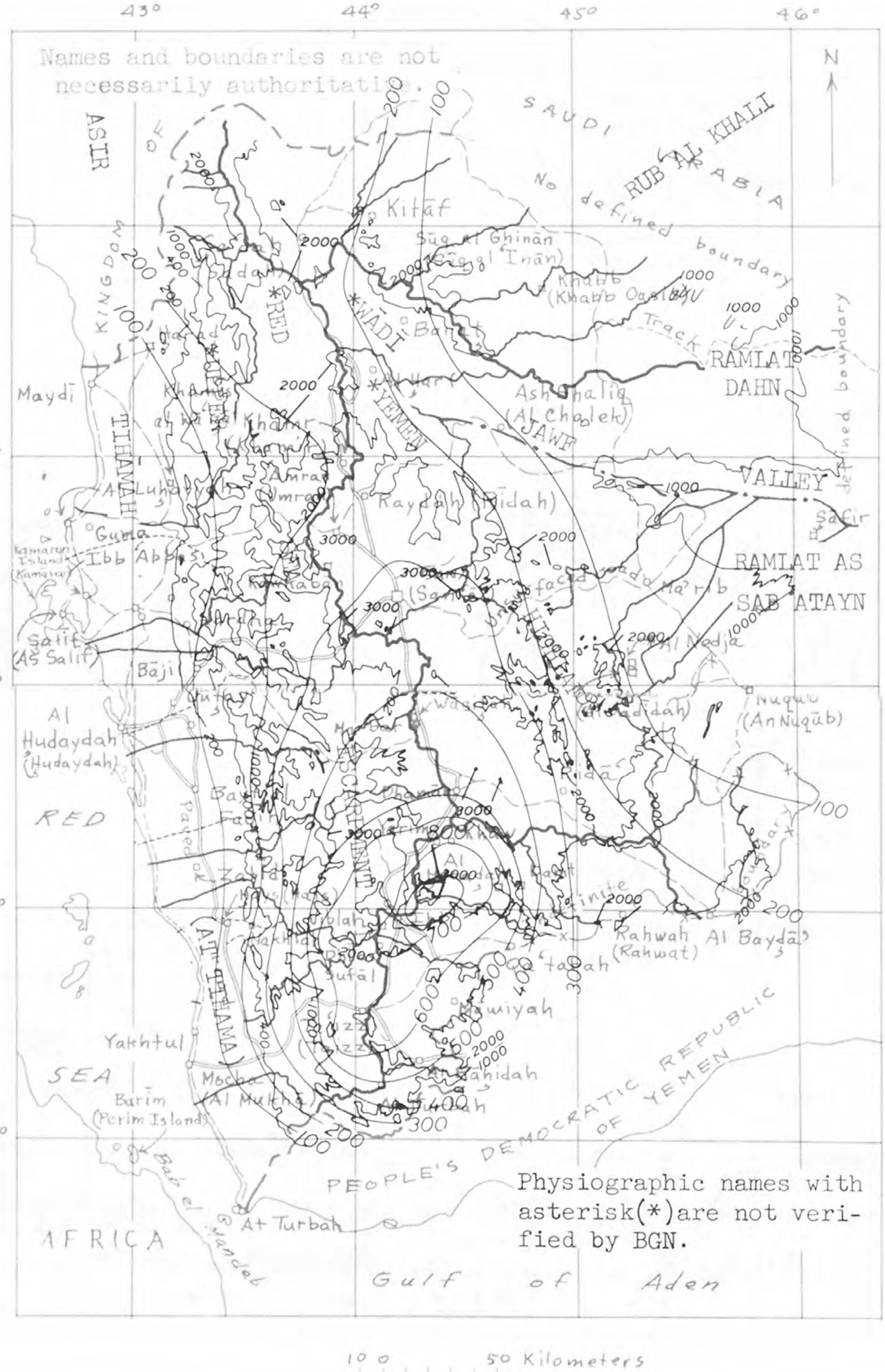

Figure 2--Small scale hydrologic map of the Yemen Arab Republic showing four catchment areas with generalized mean annual precipitation and generalized topography.

wilderness that separates it from the valley of Wādī Ḥaḍramawt, in the People's Democratic Republic of Yemen. Rubʿ al Khali lies north of the Wādī Jawf valley.

The coastal plain (the Tihāmah) is a strip of land 25 to 50 km wide, sloping gently from the base of the foothills (at an altitude of 400 m, except in the north) to the Red Sea coast. The channels of many transverse seasonal streams are incised a few meters below the colluvial, alluvial, and eluvial surfaces of the Tihāmah. Cultivated fields, irrigated with water pumped from wells, lie adjacent to many wādīs. Drifting sand and some dune fields alternate with cultivated fields in the interfluves, and salt-impregnated flats (sebkhas) are common along the coast. Coral reefs fringe the coast, particularly in the southern part of the Tihāmah.

The coastal plain rises eastward to the foothills, and its upper reaches can be traced to an altitude of 1,000 m. The intermontane part of the Tihāmah is commonly referred to as upper Tihāmah or mountain Tihāmah.

The mountainous slope, which rises from the floors of the valleys in the upper Tihāmah to the divide between westward-draining and eastward-draining streams in the interior, is referred to as the Red Sea escarpment. Total relief along the Red Sea escarpment averages 1,500 m, but west of the cities of Sana and ʿAmrān, it exceeds 2,000 m. The Red Sea escarpment, which ranges from 40 to 90 km wide, is a major orographic obstacle to southwest monsoons and also to dust blown inland from the Tihāmah. South of Ḥays, the escarpment disappears, and is replaced by lower mountain ranges that extend eastward and southward toward the People's Democratic Republic of Yemen.

The Red Sea escarpment is the catchment area for many drainage basins, and stream erosion is vigorous. Euphorbia are the dominant vegetation up to an altitude of 2,000 m; terrace cultivation on slopes is the common agricultural practice, as it is through most of the YAR.

The Yemen highlands occupy the center of the country, from the crest of the Red Sea escarpment eastward to the Wādī Jawf valley and Ramlat as Sab'atayn. The Yemen highlands are about 190 km long and 140 km wide. The rugged and complex topography, including mountain massifs and peaks more than 3,000 m in altitude, reflects the wide variety of rock types exposed in the region. Eastward, the land surface gradually slopes to a general altitude of less than 2,000 m in the alluvial valley of the Wādī Jawf and the sandy wilderness of Ramlat as Sab'atayn. North of the Wādī Jawf valley, a mountainous region above 2,000 m is the southern extension of the 'Asīr (Asir) region of the Kingdom of Saudi Arabia.

The Wādī Jawf valley occupies a 240-km long structural trough in the northeastern part of the country. Bare limestone and sandstone are exposed at the northwestern end of the trough, and its central and southern parts are covered by alluvium and windblown sand. Altitudes are generally less than 2,000 m, and less than 1,000 m along the lower reaches of Wādī Jawf, Ad Dabil (wādī) and Wādī Abrād at the northwestern end of Ramlat as Sab'atayn. The alluvial channels of Wādī Jawf are situated approximately along the axis of the trough. The flow regimen in most of these channels and tributary channels on the north and south banks of Wādī Jawf probably consists of ephemeral storm runoff only. East of the 45°30' E. meridian, the course of

Wādī Jawf abruptly ends in low sand dunes and drifting sand. Storm runoff occasionally flowing down the ephemeral channels of Wādī Abrad, northeast of Ma'rib, disappears because of high evaporation and infiltration in permeable alluvium and windblown sand. These poorly defined channels have no obvious surface connection with those of Wādī Jawf, some 15 km southeast of Al ʿAlam Aswad (1210 m), a hill of Jurassic limestone at the northwest end of Ramlat as Sabʿatayn.

The terrain in the extreme northeastern part of the YAR consists of granitic and metamorphic rocks; the region is characterized by low rainfall, and an internal drainage network oriented toward Rubʿ al Khali. Altitudes range from 1,000 to 2,000 m.

Geology

The rocks of the YAR range from Precambrian (p€) to Quarternary age. They include metavolcanic, metasedimentary, granitic and volcanic rocks, limestone, sandstone, evaporites and unconsolidated colluvial, alluvial and eolian deposits. The geology of the YAR has been described most recently by Geukens (1960, 1966). A geological map of the YAR at the scale of 1:1,000,000 accompanies Geukens' memoir (1960). A modified version of this map was used as the base for the geology of the YAR in the compilation of the geologic map of the Arabian Peninsula at the scale of 1:2,000,000 (U.S. Geol. Survey and Arabian American Oil Company (1963) (Fig. 3). Preliminary geologic maps of the YAR (Grolier and Overstreet, 1976) were prepared during the geologic phase of this program using nine Landsat-1 images as base maps.

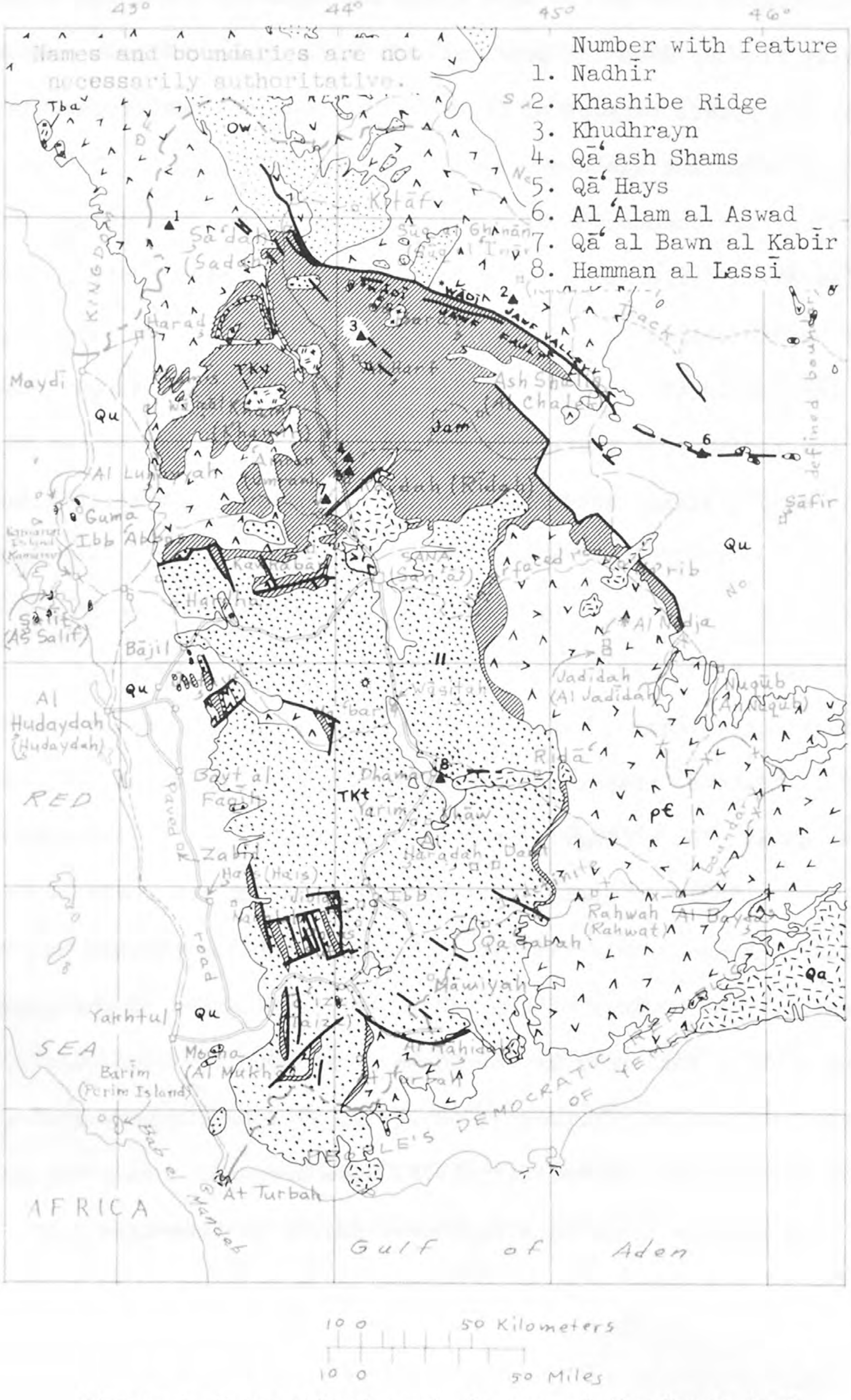

Figure 3--Generalized geologic map of the Yemen Arab Republic.

EXPLANATION*

Quaternary

Qu — Quaternary undifferentiated
Qe, Eolian sand; Qu, alluvium and related surficaial deposits

Qa — Aden Volcanic Series
May include rocks of Pliocene age

UNCONFORMITY

Tertiary and (or) Cretaceous

TKy — Yemen Volcanic Series
Tla, laccoliths; Tgr, granite; TKt, Trapp Series in places upper part overlies Medj-zir Series; Tba, Baid (Baydah)Formation, Southern Red Sea coast in Saudi Arabia near YAR border

UNCONFORMITY

TKt — Tertiary Sandstone
Tm, Medj-zir Series; Kt, Tawilah Group

UNCONFORMITY

Jurassic

Jam — Upper Jurassic
Jam, Amran Series; JKo, Kohlan Series

UNCONFORMITY

Ordovician

Ow — Ordovician Sandstone
Pw, Wajid Sandstone

UNCONFORMITY

Precambrian

pЄ — Precambrian rocks undivided
ur, Precambrian rocks undivided

Fault, dashed where approximately located

Collapsed cauldera(crater)

*Geologic symbols of Figure 3 are to consolidated geologic units. Symbols in the box geologic description are unconsolidated geologic units of, Geologic Map Of The Arabian Peninsula, 1:2 000 000, 1963

Precambrian rocks are exposed along the outer fringe of the country, mainly in erosional windows in the Red Sea escarpment, and in broad belts in the northern and southeastern regions. Metasedimentary rocks are common in the north, granitic rocks in the northeast and southeast, and metavolcanics in the south. Generally, the Precambrian rocks of the YAR form a southern extension of the Arabian Shield of the Kingdom of Saudi Arabia.

Northwest of the Wādī Jawf valley, the Wajid Sandstone (Ow), a cross-beeded sugary sandstone of Ordovician age, unconformably lies above Precambrian rocks (p€). It also forms prominent outliers in the northern part of the Red Sea escarpment and east of Ṣaʻdah.

Conglomerate, shale, and sandstone of the Kohlan Series (Jka) unconformably overlie the Wajid Sandstone. The Kohlan Series (Jko) of Early Jurassic age is best exposed around the outer edge of the Yemen highlands in the predominantly calcareous Amran Series (Jam) of Late Jurassic age. Four facies are recognized in the Amran Series (Jam) (Geukens, 1966, p. 9): (1) blue-violet fossiliferous limestone in the foothills marginal to the Tihāmah and in fault blocks farther east; (2) light-gray limestone and shale in the Red Sea escarpment, west of Sana; (3) predominantly light yellow marly limestone with thin beds of gypsum, north of Sana as far as the Wādī Jawf valley; and (4) quartzite, oolitic limestone, shale, salt, and other evaporites at Ṣāfir in the northeastern part of the country.

Sandstone of the Late Cretaceous-early Tertiary Tawilah Group (Tkt) is exposed north of Sana along the outer border of the Yemen highlands and also in the mountains southwest of Taʻizz.

Volcanic rocks were extruded during much of the Cenozoic era. The Yemen Volcanics Series (TKy) of Tertiary age cover the southern two-thirds of the country. This unit consists predominantly of felsic tuffs, interspersed with basalt layers, and is several thousand meters thick. Several granite plutons, which intrude the Tertiary volcanics are slightly younger. Lava flows of Quaternary age are exposed in four distinct lava fields: (1) northwest of Sana; (2) north and west of Ma'rib; (3) around Ridāʿ; and (4) in the southern part of the Tihāmah, inland from Mocha (Al Mukhā).

Late Quaternary gravel deposits are common near the drainage divide close to the western edge of the Yemen highlands. Late Pleistocene loess also mantles the highest exposures of volcanic rocks in the southern part of the country.

Precambrian metamorphic rocks in the YAR have been folded and faulted more intensely than younger rocks, and probably more than once. As pointed out by Geukens (1966, p. 19), basement rocks were faulted prior to the deposition of Jurassic rocks, but several large regional faults affect both the basement and the younger overlying rocks.

One of the most prominent faults is the Wādī Jawf fault along the northern edge of Wādī Jawf valley. The southern fault block of basement rocks moved downward with respect to the northern one, forming a structural basin in which deposition of Jurassic marine sedimentary rocks took place. Later reactivation of the fault resulted in vertical movement in the opposite direction. In the southern part of the YAR, the fault that controls the trend of the valley of Wādī Kaleyba, about 20 km southwest of Taʿizz, is another example of a fault which affects both basement, and overlying sediments and volcanic rocks.

The traces of the faults that affect both basement and younger rocks at the eastern boundary of the Red Sea rift are obscured by Tertiary marine deposits and overlying alluvium. Yet, Jurassic limestone of the Amran Series (Jam) crops out near Bājil in tilted fault blocks which are probably related to some stages of the formation of the Red Sea graben. Emplacement of the many mafic dikes and granitic plutons and stocks intruding Jurassic sedimentary rocks and Tertiary layered volcanic rocks is probably related in time and space to sea-floor spreading in the Red Sea, and the rotation of the Arabian Peninsula away from Africa. Aside from the many basaltic and granitic plugs in the northern part of the country, very few vents, which were the sites of Tertiary volcanic activity, have yet been identified. One of these is an 8-km wide collapsed caldera, which is located about 50 km south of Sana and was formed in felsic rocks with some layers of mafic rocks. This feature may have formed during the late phases of Tertiary volcanic activity (Grolier and Overstreet, 1976, Map IR(Y)-5). The gentle regional southerly and westerly dips of mid-Tertiary volcanic rocks in the central and southern parts of the Yemen highlands may reflect not only accumulation in tectonic basins, but also post-depositional tilting.

Monoclinal folding of the Amran Series (Jam) is common south of Ṣaʿdah, and west of Maʾrib. Piercement domes have brought Miocene-Pliocene evaporates (TKy) to the surface in the coastal Tihāmah between Al Ḥudaydah and Al Luḥayyah, and Jurassic evaporites near Ṣāfir (950^{+}m), in the Ramlat as Sabʿatayn. Quaternary marine shells strewn on the surfaces of terraces, several tens of meters above mean sea level at the sites of the Tihāmah piercement domes suggest late epeirogenic movement. The southward narrowing of the coastal plain and steeper regional slope of the Tihāmah south of Mocha also suggest late tectonic activity.

Climate

The YAR, with its land area contiguous to the Red Sea and also to the southwestern part of Rubʿal Khali, is a country of many climates (Rathjens and others, 1956). Mean annual temperatures gradually decrease from 30° Celsius (°C) in the Tihamah to 18°C in the Yemen highlands. The frost line at the latitude of Sana lies at 2,250 m and temperatures in the Yemen highlands may drop below freezing in winter.

The distribution pattern and the amount of precipitation vary with altitude (fig. 4), latitude, and distance from the Red Sea and Gulf of Aden coasts. On the Tihāmah rain falls in winter, and is less than 75 millimeters (mm). On the slopes of the Red Sea escarpment, precipitation increases with altitude, to as much as 1,000 mm per year. The Yemen highlands are characterized by two rainy seasons: 1) spring, from April to May or June, and 2) summer, the more important of the two, from July through September. Much of the rain falls in torrential showers. Rainfall in the Yemen highlands gradually decreases eastward; arid conditions prevail in Rubʿal Khali and Ramlat as Sabʿatayn.

The regional pattern of mean annual precipitation in the YAR is shown on an isohyetal map (fig. 4) prepared by Steward (1966; in Beskok, 1971, map 2). This map, based on rainfall data collected in the early 1960's at a limited

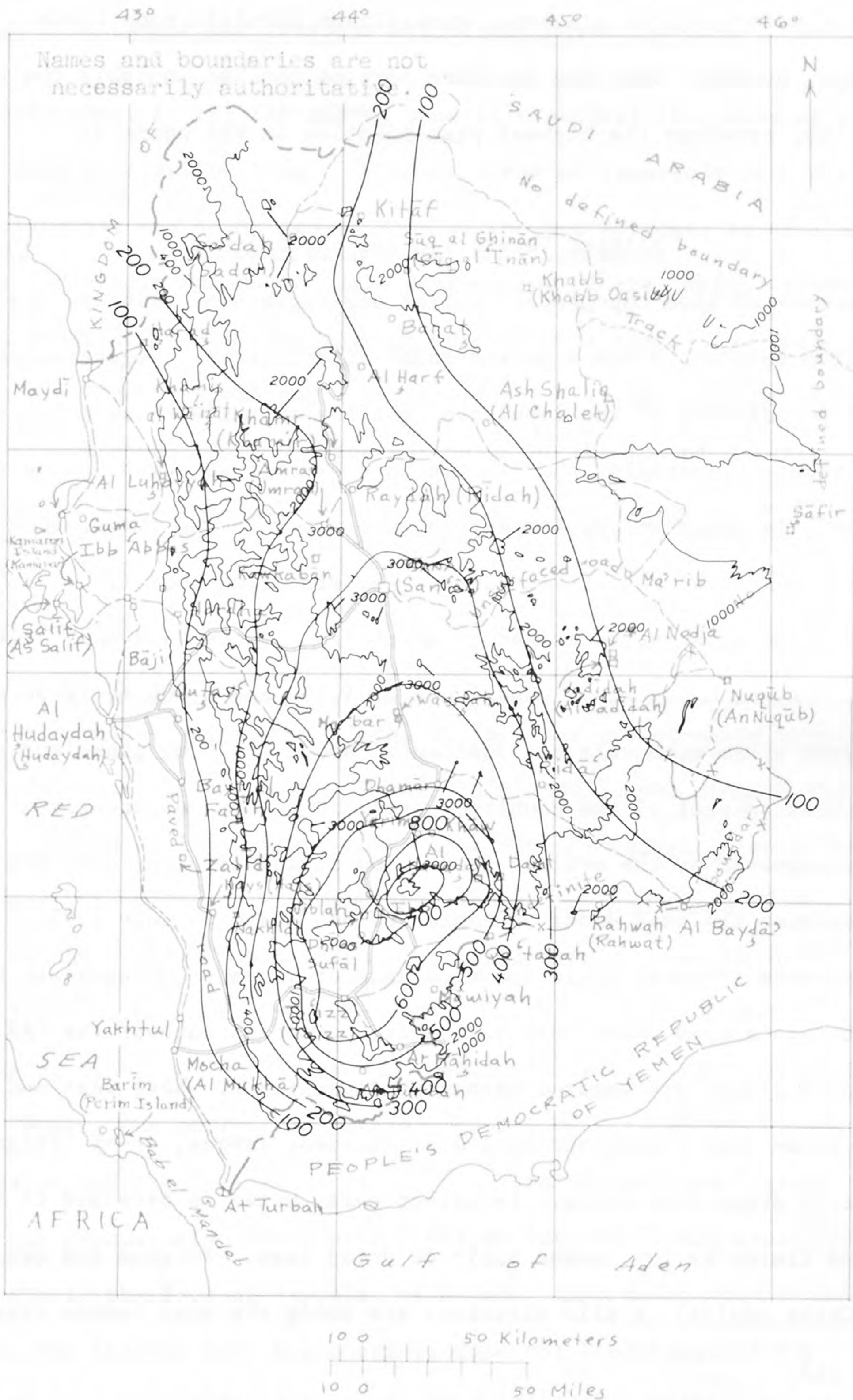

Figure 4--Small scale rainfall map of the Yemen Arab Republic showing generalized mean annual precipitation and generalized topography.

number of meterological stations, generalizes rainfall conditions. It does show, however, that the southern part of the YAR, notably the region around Ibb, receives the highest precipitation in the country.

Natural Vegetation and Agriculture

Because of high topographic relief and variety of climatic environments, vegetation in the YAR has a marked zonal distribution. Vegetation also is a sensitive indicator of the local availability of surface water and shallow ground water. Generally, the Tihāmah is a salt-grass steppe along the coast, and a prickly grass steppe farther inland; water-loving trees, such as acacias, grow along the stream banks. The elevation zone (fig. 2) between 200 and 1,250 m is characterized by myrrh, palm trees, and many cultivated plants. Higher up, between elevations of 1,250 and 2,000 m, is an ever-green zone where euphorbia are dominant. Above 2,000 m, grassland prevails. In the eastern part of the country, grass, in season apparently is common and was observed by the writers from a low-flying airplane over the low-lands between the seif dunes of Ramlat as Sabʿatayn in July 1975.

Man-made terraces built for thousands of years to bring steep hill and mountain slopes under cultivation are common throughout the YAR. Cultivated plants are watered either by diversion of sheet wash and stream flows into fields surrounded by man-made levees, or by irrigation with water drawn form wells. In either case, water is retained in the terraced fields by low levees built of dried loam. Sorghum and qat or khat (*Catha edulis*), a mild narcotic, are among the most common crops in the YAR.

Water Development and Previous Hydrologic Investigations

Water development in the YAR region goes back several thousands of years to the early stages of agriculture. There are tens of thousands of old water wells, many cisterns, and baths around some of the hot springs, as well as ancient ruins of dams. The most famous of these dams is the Ma'rib, which was built across Wādī Adhanah at a water gap west of Ma'rib, more than 2,000 years ago (Wissman, 1953, p. 85-86; Bowen and Albright, 1958). It was breached by catastrophic floods about 575 A.D. The hot baths at the top of a well-preserved volcanic cone, Hamman al Lassī (Hayd al Asī, 2870m), about 15 km east of Dhamār, were visited and described by Niehbur (1774), and a cistern near hot springs at the top of a Pleistocene volcano northwest of Sana has been described by Wissman (1953), and Fricke (1959).

Although modern investigations of the surface and ground-water hydrology of YAR may be said to have begun with Botez (1912, 1925), who studied the region between Sana and Al Hudaydah, most subsequent hydrologic studies have remained regional in character. During the 1960's, the hydrology of the central part of the Tihāmah was studied by several German investigators: Sawtschenko, 1965; Huth and Roxenberger, 1966; Quast and others, 1966; and Kraft and others, 1968. Only the last of these studies has been published to date (1976). During the early 1970's, ItalConsult, an Italian consulting firm, made an extensive hydrological study of the Sana and Al Hudaydah regions for the World Health Organization (WHO) of the United Nations (ItalConsult, 1973). During that period, the Federal Republic of Germany also maintained a technical mission in the YAR staffed with hydrologists from the Bundesanstalt fur Geowissenschaften und Rohstoffe. Beginning in mid-1974, hydrologists of the

Land Resources Division of the Overseas Development Administration of the United Kingdom have investigated the montane plains near Dhamār and in Wādī Rimaʿ for the Ministry of Agriculture of the YAR; their reports are unpublished.

In the last 15 years, WHO and agencies of many foreign governments, including the USAID, have worked in cooperation with the Yemeni government in improving water supplies in various parts of the country. Drilling programs have been initiated, and along with Yemeni personnel, foreign contractors and donors (German, American, Russian, Chinese, Iraqi, and Japanese) have drilled many modern water wells in an effort to improve municipal water supplies, irrigation, or to supply water necessary for road construction. Some of this work has been documented (Ruiz, 1966), but most of the reports are unpublished, and of limited access.

Acting for the Tihāmah Development Authority, Hungarian hydrologists (Tesco, Viziterv, and Vitok, written communs., 1971, 1973), and more recently engineers of the American firm, Tipton and Kalmbach, Inc. (written commun., 1974), have investigated the ground-water potential of the region where Wādī Zabīd flows across the Tihāmah. Tipton and Kalmbach are presently active in developing the irrigation potential of Wādī Mawr in the northern part of the Tihāmah. North of Wādī Surdūd in the Tihāmah, a large industrial state farm, where modern irrigation farming with water drawn from wells was introduced by Russian specialists, has been in operation for several years. The German technical mission also maintains an experimental state farm near Sana and two others in the Tihāmah, near the road junction between the Al Ḫudaydah-Sana highway and the road to Mocha.

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Hydrologist-in-charge for YAR, Tone Boring Co., Ltd., Tokyo, Japan; John Chilton, Hydrologist, Land Resources Division, British Ministry of Overseas Development; Rudolf Schock, Department of Geography, University of Zurich; and Peter S. Walczak, Resident Oceanographer at Al Ḩudaydah, U.N. Food and Agricultural Organization.

LANDSAT IMAGERY

Data Acquisition System

The territory of the YAR has been imaged repeatedly since 1972 by the multispectral scanners (MSS) on board the first two orbiting Earth Resources Technology satellites (ERTS-1 and ERTS-2) now called Land Resources satellites (Landsat-1 and Landsat-2). ERTS-1 was launched by the U.S. National Aeronautics and Space Administration (NASA) on July 3, 1972, and is stabilized in a near-polar orbit at approximately 907 km above the earth. ERTS-2 was launched on January 22, 1975, and has the same orbital and imaging characteristics as ERTS-1. The imaging systems or ERTS-1 have been described by Rowan and others (1974); their description is summarized below. Landsat-1 was officially retired on January 6, 1978. Landsat-3 was launched on March 5, 1978, after the compilation of this report, and therefore Landsat-3 images were not used in its preparation. The sensor systems of Landsat-3 have been modified to include panchromatic cameras, and an additional MSS band (Band 8) which acquires nighttime thermal data with a temperature resolution of 1.5°C in the temperature range from -13°C to 67°C and the spectral range of 10.4 to 12.6 micrometers (U.S. Geological Survey, 1978).

The sun-synchronous orbit of the satellite allows coverage of the same area every 18 days at the same local solar time, which is 0942 hours at the equator. Data covering selected areas (including the YAR) acquired beyond the range of receiving stations on the ground are recorded on tape carried aboard the spacecraft, and transmitted at a later time to one of three NASA receiving stations located in North America. A malfunction in the tape recorder of Landsat-1 has made delayed transmission of the digital-data stream impractical since early 1975.

Landsat Nomenclature: Band, Image, and Scene

Solar energy reflected from the earth's surface is measured in four spatially registered spectral bands through the same optical system.

Band	Wavelength (micrometers)
MSS 4	0.5-0.6
MSS 5	.6- .7
MSS 6	.7- .8
MSS 7	.8-1.1

Spatial resolution in each of the four bands averages about 80 m.

The swath imaged simultaneously in each of the four spectral bands is 185 km wide. Coverage is continuous along each orbital track, but is framed into square pictorial images. Each image covers approximately 34,200 km^2. The total Landsat-1 coverage of the YAR numbers approximately 125 individual MSS images. As of June 1, 1976, the Landsat-2 coverage available for this hydrologic study amounted to 21 MSS images.

A Landsat scene is the area of the earth surface covered by a Landsat image. This area remains nominally the same during successive passes, as long as no change in orbital characteristics occurs with passage of time; in practice, some drift in framing the image along the orbital path does occur. The number of Landsat images available for a certain region may greatly exceed the number of corresponding scenes. Outside of the United States, a scene may be imaged upon request to NASA from an investigator, every 18 days by one orbiting Landsat spacecraft, every 5 and 13 days when Landsat-1 and -2 spacecrafts were in earth orbit simultaneously, and every 9 days by Landsat-2 and -3.

A total of nine Landsat scenes, distributed over three adjacent (but not consecutive) orbital paths, cover the territory of the YAR. For ready reference, the outline of each Landsat scene mentioned in this report has been numbered (fig. 5). Numbers increase from north to south, and from the westernmost of the three orbital swaths to the easternmost. These scenes can also be referred to the world-wide index to Landsat coverage, which formalizes and uniquely identifies the geographic location over which repetitive images are centered when the satellite maintains normal positional tolerance (U.S. Geol. Survey, 1975; The World Bank, 1976). Nominal scenes are identified by three-digit orbit path and row numbers. The combined path-row number formally identifies the scene according to an arbitrary reference system first developed for Landsat coverage of Canada and extended to the whole world by the U.S. Geological Survey.

Selection and Procurement of Landsat Data

The investigation was carried out in two separate, albeit related steps: Geologic analysis preceded the hydrologic analysis. The scope of the investigation controlled the selection of the types of Landsat data which were procured. In the planning stage of the investigation, it was decided that there was no need to use computer-compatible tapes (CCT's) to enhance Landsat data, until specific geologic and hydrologic problems have been defined, and mineral prospects located. This decision seriously limited the search for reflectance anomalies due to oxidized sulfide ore deposits, either exposed or lying at shallow depth, but it had no adverse effect on the hydrologic reconnaissance of the country. So, both geologic and hydrologic analyses were made using prints and transparencies of Landsat images available from the EROS Data Center, Sioux Falls, South Dakota 57198.

Geomorphic analysis calls for distinctly different criteria in the selection of Landsat images than lithologic and hydrologic analysis. Low-sun elevation above the horizon, which optimizes length of shadows, enhances topographic detail and tonal contrast, is the overriding criterion in the selection of Landsat images for geomorphic and structural analysis. Consequently, nine Landsat-1 images (fig. 5) corresponding to the nine Landsat scenes covering the YAR were selected for geologic analysis out of a total of 125 images available, because of the time of imaging (close to the 1972 winter solstice in the period from November 18, 1972 to February 14, 1973) and of other factors such as image availability, freedom from clouds, and image quality. Geologic mapping was accomplished on transparent overlays placed over three-band false-color Cibachrome composite prints at the scale of 1:500,000. Also while the nine Landsat-1 images were being mapped geologically, a black and white mosaic of Landsat images was hand-assembled by the Special Maps Center, Topographic Division, U.S. Geol. Survey, Reston, Virginia, and completed in September 1977. Currently, a black and white mosaic of digitally processed Landsat images which will include the territory of the YAR, is being prepared by the USGS Image Processing Facility, Flagstaff, Arizona, on behalf of the Office of International Geology (OIG), USGS, and the Directorate General of Mineral Resources (DGMR), Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia.

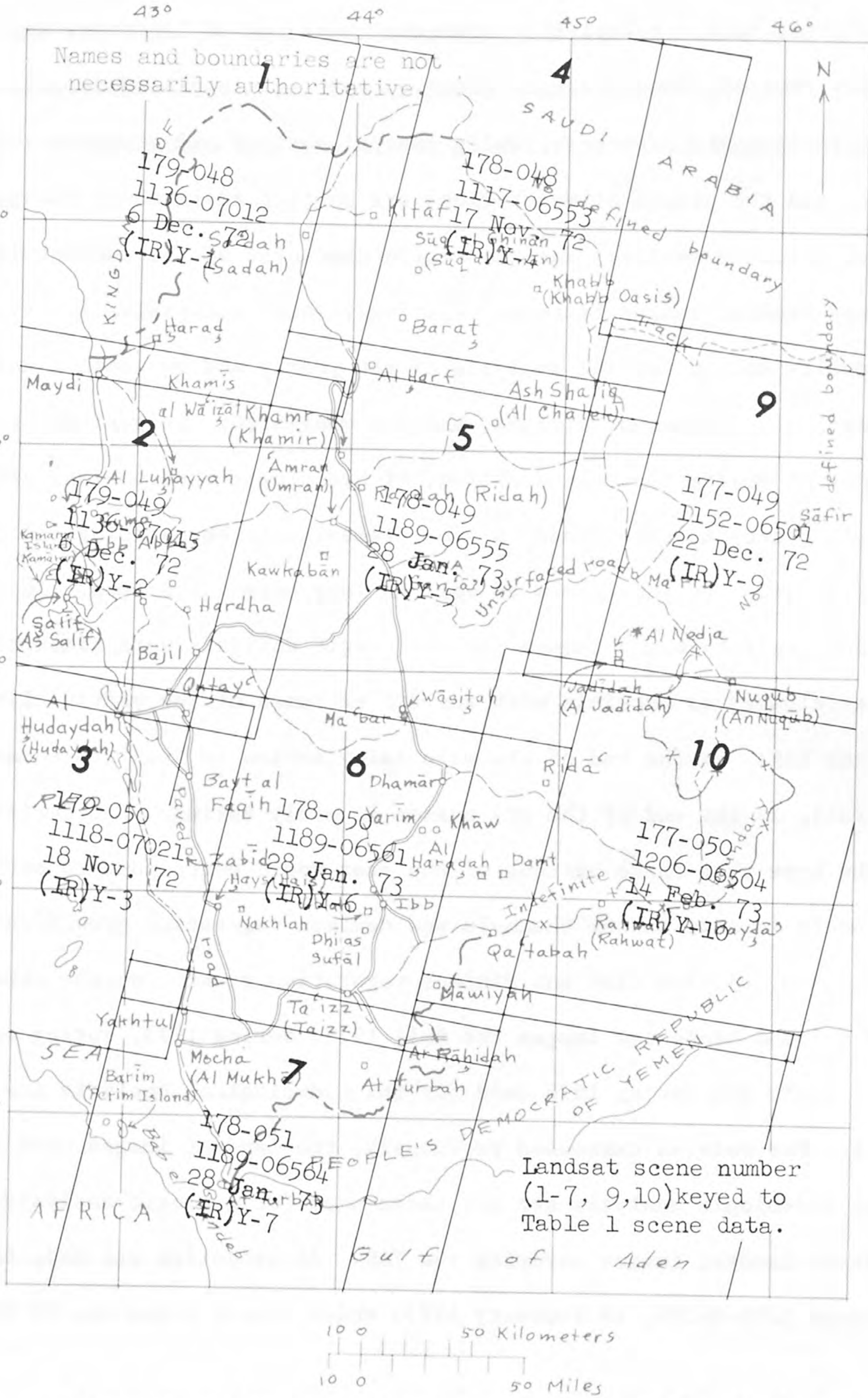

Figure 5--Index map of the Yemen Arab Republic showing outlines of Landsat nominal scenes covering the YAR.

In contrast to the relatively permanent character of landforms and rocks and the slow rate of change brought about by most erosional and depositional processes, the dynamic processes, which control surface and ground-water conditions, and the growth of vegetation, are subject to seasonal changes and longer-term climatic cycles. The repetitive character of the Landsat imaging system makes Landsat images taken at relatively short successive intervals of time ideally suited for the analysis of the yearly and seasonal fluctuations in the hydrologic regimen of streams, and for monitoring the periodic growth and dormancy of vegetation. In addition, if hydrologic observations are to be meaningful, they must be timed to some elements of the hydrological cycle which are suitable for short-term as well as long-term comparison. In this context, the Landsat images chosen for hydrologic analysis were timed to coincide as closely as possible with the two extremes of the yearly climatic cycle in the YAR: 1) the end of the main rainy season in the late summer or early fall, 2) the end of the dry season in early spring. The decision was made in the hope that these periods of the year would correspond to periods of high-runoff in some stream channels and maximum vegetation growth on land, on the one hand, and low flow and minimal vegetation growtn, on the other. The Landsat-1 and Landsat-2 images for fall 1972, spring 1973, spring-summer 1975, fall 1975, and spring 1976 used for the hydrological analysis are listed in table 1. For reasons expressed previously, the Landsat images used in this report for hydrologic analysis are not those used for geologic analysis or for the mosaic of Landsat images covering the YAR. An exception was made for Landsat image 1206-06504, 14 February 1973, which covers scene no. 10 (fig. 5), and was used for both geologic and hydrologic analyses because of its exceptionally good quality, and also because a Landsat image with a lower sun angle for that scene was unavailable at the time the mosaic was being assembled.

TABLE 1.--Landsat-1 and Landsat-2 images used in the analysis of yearly and seasonal fluctuations of vegetation, streamflow, and underflow (1972-1976) in the Yemen Arab Republic.

Landsat scene outline No. (see fig. 5)	Path/row No.	Landsat ID No.	Fall 1972 (high runoff)	Landsat ID No.	Spring 1973 (low flow)	Landsat ID No.	Fall 1973 (high runoff)	Landsat ID No.	Summer 1975 (high runoff)	Landsat ID No.	Fall 1975 (high runoff)	Landsat ID No.	Spring 1976 (low flow)
1	179-048			1244-07014	Mar. 24	1406-07000	Sept. 2			2276-06475	Oct. 25		
						1424-06593	Sept. 20						
2	179-049	1010-07004	Aug. 2			1406-07002	Sept. 2			2276-06481	Oct. 25		
						1424-07000	Sept. 20						
3	179-050	1010-07011	Aug. 2			1406-07005	Sept. 2			2276-06484	Oct. 25		
		1082-07013	Oct. 13			1424-07002	Sept. 20						
4	178-048	1045-06545	Sept. 6			1423-06535	Sept. 19	2149-06434	Jun. 20	2257-06421	Oct. 6		
		1063-06544	Sept. 24			1441-06533	Oct. 7	2185-06432	Jul. 26				
5	178-049	1045-06551	Sept. 6			1423-06542	Sept. 19	2149-06440	Jun. 20	2257-06424	Oct. 6		
		1063-06551	Sept. 24					2167-06440	Jul. 8				
6	178-050	1045-06554	Sept. 6			1423-06544	Sept. 19	2149-06443	Jun. 20	2257-06430	Oct. 6		
		1063-06553	Sept. 24										
7	178-051	1045-06560	Sept. 6	1255-06570	Mar. 5	1423-06551	Sept. 19			2293-06431	Nov. 11		
		1063-06560	Sept. 24										
9	177-049	1044-06493	Sept. 5					2130-06381	Jun. 1	2274-06364	Oct. 23	2400-06350	Feb. 26
												2418-06343	Mar. 15
10	177-050	1044-06495	Sept. 5	1206-06504	Feb. 14			2130-06384	Jun. 1	2274-06371	Oct. 23	2400-06352	Feb. 26
								2148-06385	Jun. 19				

METHODS OF ANALYSIS

The work procedure followed during both the geologic and the hydrologic analysis phases of the program consisted of bibliographic search, image interpretation supported by interpretation of available topographic maps, and reconnaissance field checking.

Bibliographic Search

The geologic and hydrologic literature covering the territory of the YAR is scattered through the scientific periodicals of several countries (mostly France, Germany, and the United States). An off-line computerized bibliographic citation list generated by GEOREF and originiating with System Development Corporation (SDC), Santa Monica, California, was most useful at the start of the investigation in retrieving reports published during the last 10 years.

Image Interpretation

Geologic Analysis

Geologic mapping on three-band false-color Cibachrome prints of each of the nine Landsat-1 images enlarged to the scale of 1:500,000 was checked for accuracy against black and white positive transparencies at the scale of 1:1,000,000 of band 7, the near infra-red band where terrain contrast between mafic and felsic rocks is greatest. Black and white positive transparencies at the same scale of band 4, in which penetration of clear water by solar radiation in the blue-green portion of the spectrum occurs down to several fathoms, were utilized to check the extent of coral reefs observed along the Red Sea coast. Even though albedo and color are ambiguous parameters for distinguishing geologic materials, a preliminary geologic map of the YAR was produced (Grolier and Overstreet, 1976) at 1:500,000 scale, that showed a larger amount of geologic data than had been possible heretofore. This positive result was possible because of 1) the relatively small scale of the geologic map (1:500,000); 2) the vivid contrast between some of the more widespread rock units in the country (i.e., limestone in contrast to volcanic rocks; young and unweathered volcanic rocks in contrast to older and/or weathered rocks, and alluvium and eolian sand); 3) relative sparsity of vegetation and lack of thick chemically weathered soils; and 4) the unusually high regional relief (more than 3,000 m) which, in some places, allowed three-dimensional structural analysis on a monoscopic image. The high quality and photographic fidelity of the Cibachrome color prints made of each image, were a great help in the geologic analysis.

Surface Water and Vegetation

The interpretations given of the hydrologic features of the YAR can be considered only as qualitative and preliminary because of some of the engineering characteristics built into the Landsat orbiting and imaging systems put definite constraints on an evaluation of the hydrologic features of any arid or semiarid land. The irregular repetitiveness in imaging the scenes in the YAR, and frequent cloudiness make the imaging of sheet-wash flows and direct surface runoff in ephemeral streams -- processes which figure so importantly in the yearly renewal of water resources in an arid land -- a matter of chance. Likewise, the spatial resolution of the system (approximately 80 meters) is inadequate for detection of most ground-water discharges. Only very large springs or seeps can be detected on the Landsat-1 and -2 images. Numerous small seeps, where they are close to one another, can be detected as a group, but cannot be discriminated as individual seeps or springs by the interpreter.

A review of irrigation and drainage practices in the YAR, however brief, makes for a better understanding of water occurrence, and the difficulties encountered in observing it. Flood irrigation is the traditional practice in the Yemen highlands and on mountain slopes, as it is elsewhere in many arid regions. Regulated irrigation through diversion canals is practiced to some extent near perennial reaches in some wādīs and at the head of the Tihāmah. In both environments irrigation with surface water is supplemented by water drawn from wells or diverted from springs. Where flood irrigation is practiced on terraced fields, advantage is taken of natural overland flow moving as sheet wash and in rills over valley slopes and valley floors. Overland flow is channeled and stored in terraced fields surrounded by levees of dried mud, or walls of roughly piled uncemented stones surrounding the fields. Once the moisture capacity of the soil is reached, excess water is allowed to escape to the next terrace below through a breach in the levee or the openings between stones in the walls. Excess water in the bottom terrace moves down toward the nearest wādī channel or evaporates. To record such a complex sequence of events on a Landsat image, and then to detect it through image analysis by visual means are difficult, and not always successfully accomplished tasks.

The water resources of any region, that is, the total supply of water available, depend on the annual water budget, which expresses the balance between the various components of the hydrologic cycle. On the one hand, there is the annual increment of rainfall as a credit, whereas on the other hand there are annual runoff, infiltration, percolation through soil, changes in storage of water in the ground, seepage of ground water to sea or interior basins, and finally evaporation and transpiration as debits. In the YAR, only the input to this system, the annual rainfall, has been measured (to some degree). Evaporation is known to be high, but it has not been measured; infiltration does occur--and probably could be estimated, but has not been measured.

It is the purpose of this report to describe where concentrated runoff takes place, where soil moisture is readily available, and where ground water is stored at shallow depth (as indicated by growing vegetation), so that recommendations can be made as to how the other elements of the hydrologic cycle can be measured. The report describes the occurrence (rather than the renewal) of soil moisture and the surface and shallow ground water. It also describes the direction of flow, water quality (to some extent), and yearly fluctuation in the occurrence of water between the two main periods of high runoff and low flow. The report does not give quantitative evaluations for frequency and amount of seasonal and yearly renewal, annual stream flow or well yield, nor the chemical quality of water. The year 1975 was a relatively "wet" year compared to the previous 3 years, although total precipitation was not much greater than the long-term average. It was selected as the temporal base of reference, during which "normal" surface water distribution and "normal" plant growth are compared with conditions during previous and subsequent years. On the basis of the hydrologic evidence shown on Landsat images, the years 1972 and 1973 are interpreted as being anomalously dry years and so were rejected as reference years. It is possible that these years are representative of the prolonged drought which affected a belt of the northern tropical zone extending at least from western Africa to southwestern Asia.

The initial step in this preliminary investigation of water resources in YAR was the preparation of a small-scale topographic map, which could serve as a base map on which the boundaries of catchment areas and drainage basins, precipitation and geologic data could be overlain. The 200-m, 400-m, 1,000-m, 2,000-m and 3,000-m contours were traced off topographic maps at the 1:250,000 scale (United Kingdom, Ministry of Defence, Mapping and Charting Establishment, 1974), and reduced to an appropriate scale. The divides between drainage basins were delineated on a false-color mosaic of landsat images covering the YAR at the 1:500,000 scale. Where regional relief was low and did not allow visual identification of divides on the mosaic, boundary lines were transferred to the drainage basin map from topographic maps. A small-scale map of the drainage network was also prepared in the same manner (figure 6). The resulting drainage basin map, on which four catchment areas and the major drainage basin in the YAR are outlined (plate 1) was then reduced and overlain on the topographic base map (figure 2). The isohyetal map of the YAR (figure 4) is also superimposed on the small scale topographic map. All these maps are at the same scale and may be readily compared to one another in order to bring out such relationships as may exist between location, altitude, shape and size of watershed on one hand, and precipitation and rock types on the other hand.

Figure 6--Small-scale map of the Yemen Arab Republic showing four catchment areas, the major drainage basins, and the drainage network within them.

The next step was to identify, locate, and describe those drainage channels, where streamflow could be observed. Lastly, areas supporting vegetation also were identified as a basis for inferring other hydrological conditions. Only two of the four bands available for each scene were used in this analysis: Band 7 was utilized because there is little or no reflection of incident solar radiation from water in this spectral region, and thus the water appears dark in a positive black and white print or transparency; band 5 was used because, within the red region of the spectrum, chlorophyll and carotene absorption of incident solar radiation reduces the magnitude of reflectance, and vegetation appears dark gray on a positive black and white print. Band 6, which can be used to identify wet and saturated soil (Deutsch and others, 1973) was not used, because the two principal objectives of the analysis are identification of streamflow and vegetation.

Vegetation and water are directly mappable on black and white transparencies or prints of bands 5 and 7. Nevertheless, two-band false-color composites were prepared for each scene, using Diazo color foils in order to enhance contrast by addition of color. By superposing the two bands upon each other, using foils suitable for additive color techniques, water and vegetation appear on the false-color composite in the dark hue of the colored band in which their reflectance is least. This part of the analysis was accomplished at a scale of 1:1,000,000, to conform to available laboratory equipment.

The vegetated areas of the YAR are important to a report otherwise devoted to water resources because plants are an excellent indicator of water availability during their growing season. Natural vegetation and agricultural crops were identified separately in some places, and lumped together where the size of cultivated fields is below the resolution of the Landsat imaging system, and the geometric pattern characteristic of cultivation cannot be detected. Even where a definite pattern of cultivation does not emerge from the analysis of a Landsat image, some inferences can still be drawn from the environment in which plants grow. "Light forest" in the mountains can be generally inferred from the characteristically diffuse color value superposed on an otherwise drab, grayish, rugged terrain. Yet, there is no way at the scale of this visual analysis to state the percentage of terraced irrigated fields planted with qat(khat), or with sorghum, which is included with trees and succulents growing wild in the "light forest." Similarly, vigorous seasonal plant growth in alluvial valley floors takes on different meanings depending on site location, which in turn may reflect one of the many cultural, ecological, or economic patterns of human activities. In the valleys of wādīs near the drainage basin divides between catchment areas (where precipitation is relatively high because of altitude, and population density is also high), spectral evidence of vigorous seasonal plant growth implies agricultural crops. At lower altitudes in the Yemen highlands, particularly in the basins of wādīs draining Precambrian crystalline rocks, where aridity is greater than in the mountains, and population density may be low, seasonal plant growth, particularly spot vegetation at times of low flow, may imply that phreatophytes are growing in alluvium, drawing water from shallow ground water, or simply that plants are thriving on soil moisture replenished by the last storm runoff, or from seeps and springs too small to be detected.

In this reconnaissance survey of the vegetation in the YAR, the objective was to interpret the spatial distribution of plants as observed on Landsat images, and to infer from it the sources of the water (soil moisture, surface or ground water) utilized by plants. The presence of soil moisture or ground water available for plant growth is inferred from the presence of vegetation. The plants themselves are described only in very general terms, even at the community level.

Reconnaissance Field Checking

Two field trips were made in connection with this program. The first trip, which included aerial and ground reconnaissance was made between June 16-July 13, 1975, jointly with W. C. Overstreet, USGS economic geologist. During this trip it was possible to check the accuracy of the preliminary geologic map (Grolier and Overstreet, 1976), and to appraise several mineral prospects. A low-altitude aerial reconnaissance of the country was made during the first week in the field. It helped to relate erosional, textural and tonal patterns to specific rock types, to observe stratigraphic relationships, and to prepare for the ground reconnaissance. Laterite, which occurs in the Asir region of the Kingdom of Saudi Arabia, was sighted for the first time in the extreme northern part of YAR from the airplane. Darkening of limestone along contacts with lamprophyric dikes, which had been observed on Landsat-1 images, was confirmed from the airplane and later verified on the ground. The ancient dam across Wādī Adhanah near Ma'rib was overflown, and observations were made from the air of the ruined control gates and irrigation canal partly buried by drifting sand. Field checking on the ground was limited to a reconnaissance along the major road network of the YAR: Sana-Ta'izz-Mocha, Al Ḩudaydah, Sana; to a round trip Sana-Şa'dah-Sana; and a few side trips around Sana; Ta'izz, and Şa'dah.

The second trip, February 1-29, 1976, afforded an opportunity to collect rock and water samples in regions not visited during the first reconnaissance. It allowed close observation of several late Tertiary piercement domes on the Tihāmah near Al Luḩayyah, sampling of several water wells, and of pre-Cambrian rocks exposed in the southeastern part of the YAR, along the road between Ridā' and Al Bayḑā'. Rock and water samples collected during the second trip had not yet been analyzed as of this writing.

REGIONAL OCCURRENCE OF SURFACE WATER AND VEGETATION IN THE YEMEN ARAB REPUBLIC

Only streams, one spring, and several seeps were identified during the analysis. No lakes or ponds were detected at the 1:1 million scale of the analysis. Although there are many kinds of springs, only a few are described in this report. The terms used to describe them and some of the phenomena and processes associated with springs and streams are explained in a glossary, in Appendix I at the end of this report.

There are four main catchment areas in the YAR. Listed in order of increasing annual precipitation, they are: (1) Rub' al Khali, (2) Wādī Jawf (Arabian Sea), (3) Red Sea, and (4) Gulf of Aden.

The divides between catchment areas and those between smaller drainage basins need not coincide with ground-water divides. Only catchment area divides are described below. Detailed hydrologic investigations are required in a semiarid country such as the YAR to locate ground-water divides accurately. One divide at the top of the Red Sea escarpment separates the drainage basins draining toward the Red Sea from those draining eastward toward Rubʿ al Khali, Ramlat as Sabʿatayn, and southeastward toward the Arabian Sea. This catchment area divide is parallel to the general orientation of the Red Sea coast, and its closest approach to the coast, 110 km, is west of ʿAmrān. The highest altitudes in the YAR are along this divide, which rises above 3000 m southwest of ʿAmrān, near Jabal Ḥaḏūr ash Shaykh (3350 m), also southwest of Sana at Jabal an Nabī Shuʿayb (3620 m), and northeast of Ibb, at Jabal Manār (3350 m). Altitudes along the divide are in excess of 2000 m except at the northern and southern ends. The lowest pass at the northern end is located 6 km south of Jabal al Khaṭṭārīn (2130 m); there, the divide between the Wādī Mawr and Wādī Jawf valley drainage basins is below 1750 m. At the southern end, 30 km northeast of Taʿizz, the divide is at 1650 m elevation.

The divide between the Rubʿ al Khali and the Wādī Jawf catchment areas begins at the Red Sea catchment divide, 17 km south of Ṣaʿdah, and stays a few kilometers north of the fault zone, which borders the northern side of Wādī Jawf valley (figs. 2 and 3). The Gulf of Aden-Wādī Jawf (Arabian Sea) catchment divide begins at the Red Sea catchment area divide about 10 km south of Dhamār, and trends eastward for about 50 km, generally above 2000 m. The four main catchment areas in the YAR and the drainage basins within them are shown in Plate 1 which is based on a mosaic of nine Landsat-1 images covering the Yemen Arab Republic at the 1:500,000 scale.

The Rubʿ al Khali catchment area receives the least precipitation, from 100 to 250 mm per year in the western part, and less than 100 mm per year in the eastern part. Similarly, the eastern part of the Wādī Jawf valley drainage basin gets less than 100 mm rainfall per year. However, in the higher and westernmost part of the basin, between the cities of Sana, Dhamār, and Ridā', annual rainfall ranges from 350 to 550 mm. Annual rainfall in the northern part of the Red Sea catchment area (Fig. 4) is generally less than 300 mm, but south of the Wādī Surdud drainage basin, rainfall gradually increases from 300 mm to as much as 700 mm in the Red Sea escarpment, southwest of Ibb. The catchment area draining toward the Gulf of Aden in the extreme southern part of the country (pl. 1 and fig. 2) receives from 600 to 800 mm of rainfall per year.

In this report, all descriptions of surface water, and indirectly ground water through the distribution of vegetation, were obtained from analysis and interpretation of Landsat images. The occurrence of water and vegetation in each of the individual drainage basins which make up the four catchment areas of the YAR is described in the order of increasing annual rainfall for each region. A list of the drainage basins in that order is shown in table 2.

TABLE 2.--Catchment areas and drainage basins (in order of increasing rainfall) in the Yemen Arab Republic.

Catchment area	Drainage basin (from North to South)
Rubʿal Khali (Ar Rabʿal Khālī)	1. Wādī Najrān[1]
	2. Wādī Khadwān
	3. Wādī ʿImārah (W. Imara)-Wādī Amlaḥ
	4. Wādī Qa ʿīf (W. Quʿayf)-Wādī Silbah (W. Silba)
	5. Wādī Khabb (W. Khubb)
	6. Wādī Amwāḥ-Wādī Khalīfayn
Wādī Jawf (Arabian Sea)	1. Wādī Madhab
	2. Wādī Jawf valley
	3. Wādī al Khārid
	4. Wādī al Furdah, Wādī al Jufrah, Wādī Raghwān (W. al Mukhaynia)
	5. Wādī Adhanar
	6. Wādī al Khāniq (W. Manqai)
	7. Small unnamed wadi drainage basins northeast of Jabal Omrikha
	8. Wādī Ḥarīb[2]
	9. Wādī Bayḥān[3]
	10. Wādī Markhah[3]

1 The lower part of this basin is located in Kingdom of Saudi Arabia

2 The lower part of the basin is located in the People's Democratic Republic of Yemen

3 The upper and lower parts of these two basins are located in the People's Republic of Yemen

TABLE 2.--Catchment areas and drainage basins (in order of increasing rainfall) in the Yemen Arab Republic -- continued.

Catchment	Drainage basin (from North to South)
Red Sea	1. Wādī Difā'ah (W. ad Dafa)-Wādī Hanabah
	2. Wādī Ḍamad
	3. Wādī Jīzān (W. Qīzān)-Wādī Ma'bār
	4. Coastal stream drainage basins A
	5. Wādī Mawr
	6. Coastal stream drainage basins B
	7. Wādī Surdūd
	8. Coastal stream drainage basins C
	9. Wādī Sihām
	10. Coastal stream drainage basins D
	11. Wādī Rima'
	12. Wādī Zabīd
	13. Coastal stream drainage basins E
	14. Coastal stream drainage basins F
	15. Coastal stream drainage basins G
	16. Wādī al Ghayl-Wādī Rasyān
	17. Coastal stream drainage basins H
Gulf of Aden	1. Wādī Ḥamrā', Wādī Ḥarīb, and Saylat Sīḥ
	2. Wādī Banā
	3. Wādī Tuban[4]
	4. Gulf of Aden coastal stream drainage basins[4]

4 The lower parts of these basins are located in the People's Democratic Republic of Yemen

Rubʿ al Khali (Ar Rabʿ al Khālī) Catchment Area

Surface water.--The presence of surface water was found in only two of the six drainage basins identified in this area, namely in the Wādī Khadwān drainage basin and the Wādī ʿImārah-Wādī Amlaḥ drainage basins. All streams in this catchment area are ephemeral, with the exception of the short intermittent reaches of Wādī Khadwān and the tributary to Wādī ʿImārah described below.

Vegetation--Some vegetation was detected in all drainage basins, but there is appreciably less vegetated area in the northeasternmost basins than in the others. As expected, there are wide seasonal fluctuations in growth, but yearly differences occur also.

Wadi Najrān Drainage Basin

Surface water.--None.

Vegetation.--Vegetation is limited to valleys in the Ṣaʿdah region: in the valleys of Wādī Dammar (W. Dammer) and Wādī ʿAbdī, south and southeast of Ṣaʿdah; in the valley of Wadi ʿIlāf, southwest of Ṣaʿdah; in the valley of Wādī Agnām, and sporadically in the valley of Wādī Ṣubr. Vegetation also grows away from the wādīs, in spots on the Wadjid Sandstone. Vegetation growth was most vigorous in October 1975, less so in September 1973.

Wādī Khadwān Drainage Basin

Surface water.--Wadi Khadwān is an intermittent stream that had some water at the surface or ground-water underflow in October 1973, June 1975, and October 1975. Yearly and seasonal variations are great. There was no water in September 1972, and there was less water in July]975 than in June 1975.

Vegetation.--There are some irrigated fields in the upper (southern) part of the valley of Wādī Khadwān. Plant growth was most vigorous in October 1975.

Wādī ʿImārah (W. Imara)-Wādī Amlaḩ Drainage Basins

Surface water.--In the drainage basin of Wādī ʿImārah, water was at the surface or as underflow in the short reach of an intermittent tributary draining into Wādī ʿImārah at the following times: September 1972, September 1973, June 1975, and October 1975. Yearly and seasonal variations are prominent: streamflow was most obvious in September 1972 and October]975. Water in the reservoir upstream from a dam across the headwaters of Wādī Az̧lah, a south-bank tributary of Wādī Amlaḩ, was not detected at the scale and resolution of the Landsat images analysed.

Vegetation.--Vegetation is restricted to (1) the valley floor in the northeast-trending valley 8 km north of the village of Kitāf, and also in the plain near Kitāf. This valley joins the upper part of the valley of Wādī ʿImārah; (2) the valleys of Wādīs al ʿAqīq, Amlaḩ, and Az̧lah. Irrigation farming is probable in those valleys. Vegetation was most vigorous in 1973 and 1975, particularly at the mouths of Wādīs ʿAqīq and Az̧lah, where both wādīs enter the large alluvial plain at the edge of the desert.

Wādī Qaʿīf (W. Quʿayf)-Wādī Silbah (W. Silba) Drainage Basins

Surface water.--None.

Vegetation.--There is vegetation in valley floors within a distance of 10 km north and east of the village of Sūq al Ghinān (Suq al ʿImān). Discontinuous patches of vegetation grow at the base of the foothills in the valley of Wādī Qaʿif. There is a marked seasonal change in the vigor of plant growth between July and October 1975, and a marked increase in plant growth between 1972 and 1973.

Wādī Khabb (W. Khubb) Drainage Basin

Surface water.--None.

Vegetation.--Vegetation is restricted to Khabb (Khabb Oasis), in the valley of Wādī Khabb, and to the valley floor of a northeast-trending tributary to Wādī Khabb, about 4 km west of Khashiba Ridge (1770 m). There are also faint traces of vegetation in small valleys in the western part of this drainage basin.

Wādī Amwāḥ-Wādī Khalifayn Drainage Basins

Surface water.--None.

Vegetation.--Some vegetation was present in the valley floor of an unnamed wādī, west of long. 45° in September 1972, October 1973, and less in June 1975. This vegetation occurred in discontinuous patches ranging from a few hundred meters to 3 to 4 km long. In October 1975 there were some faint traces of vegetation in the valley of Wādī Shuqbān.

Wādī Jawf (Arabian Sea) Catchment Area

The Wādī Jawf catchment area is the largest in the YAR. It includes all the drainage basins tributary to Wādī Jawf and its southeasterly extension across Ramlat as Sabʿatayn. It is characterized by the extreme asymmetry of long south-bank tributaries and short north-bank tributaries. This catchment area undergoes wide-ranging yearly and seasonal fluctuations. Its hydraulic regime, its ground-water hydrology, and its vegetation therefore are sensitive indicators of climatic fluctuations in the YAR.

Wādī Madhab Drainage Basin

Surface water.--The Wādī Madhab drainage basin is interpreted as containing the headwaters of Wādī Jawf. In October 1975, there was surface water in two wādīs tributary to Wādī Madhab and in pools between riffles in the lower course of Wādī Madhab. In June 1975, water was in the lower course of Wādī Madhab, but not in the two tributary wādīs described above. Water conditions in September 1972 were similar to those in October 1975, but no surface water whatsoever was present in September 1972. No streamflow in any of the other wādīs was detected on any of the Landsat images examined.

Vegetation.--Vegetation is present in the valley of Wādī Madhab for 7 km southeast of Jabal as Ṣafrā' (2030 m), and also near the city of Baraṭ, in the valleys of wādīs tributary to Wādī Madhab.

Wādī Jawf Valley Drainage Basin

The Wādī Jawf, the main watercourse of the Wādī Jawf (Arabian Sea) catchment area, is ephemeral. In the north-bank tributaries to Wādī Jawf, neither surface water nor vegetation was evident. All streams there must be ephemeral. In contrast, three south-bank tributary wādīs to Wādī Jawf: Wādī al Khārid, Wādī Adhanah, and Wādī Ḥarib are perennial or intermittent along some reaches, even though these three streams are ephemeral for tens of kilometers upstream from their junction with Wādī Jawf.

Wādī al Khārid Drainage Basin

Surface water.--Wādī al Khārid is the westernmost of the south-bank tributaries to Wādī Jawf. Wādī Ḍahr and Wādī as Sirr, which debouch in the Sana basin, possibly a closed interior basin, are included within the Wādī al Khārid basin for descriptive purposes only.

Water was flowing in Wādī Ḑahr in October 1975, but not in June and July 1975, nor 1972 and 1973. In Wādī as Sirr, water flowed in October 1975, September 1973, and to a lesser extent in September 1972 and June 1975. At the 1:1,000,000 scale of this analysis, it was difficult to discriminate between streamflows in Wādī Ḑahr and Wādī as Sirr, and in irrigation ditches diverting water from them. A strong seasonal and yearly variation in runoff is indicated, as is also true for the flow of Wādī al Khārid. Wādī al Khārid is an ephemeral stream in the upper part of its course, but for 12 km upstream from the 90° bend, where it enters the Wādī Jawf valley, it is an interrupted stream with intermittent stretches of water in pools between dry reaches. In this part of its course Wādī al Khārid is alternately a gaining and losing stream. Water was flowing or standing there in October 1975, in September 1973, much less in July 1975, none in June 1975, and none in September 1972. In October 1975 surface water flowed in the channel of Wādī al Khārid for 48 km downstream from the 90° bend to where it enters the Wādī Jawf valley. There are strong annual and seasonal fluctuations in surface flow there. Wādī al Khārid was an intermittent and interrupted stream in June 1975 and in September 1972. It flowed only for 5 km downstream from the bend in July 1975, but in September 1973 flowed as far downstream as the junction with Wādī al Jufrah.

Vegetation.--Farming is widespread in the Sana plain, and in the valleys jacent to it. The largest of these farmed areas are in the valleys of Wādī as Sirr northeast of Sana, and Wādī Ḑahr northwest of it. The plains of Qāʿ Hays and Qāʿash Shams, northeast of Raydah (Rīdah), and the valley of Wādī Aṯṯāf (Ghayl Hirran) also are intensively farmed. Other valleys farther north are intensively farmed, and seasonal plant growth is prominent there. These are: The ʿAmrān valley, in the Qāʿal Bawn al Kabīr (Beni Awni al Kabir), and adjacent valleys such as those of Wādī Ḥaydān, Wādī Mansib, and the lower reaches of Wādī Qumāmah and Wādī Salab. The plains in the district of Al Ḥarf also show evidence of vigorous seasonal plant growth, as follows: 1) the plain and valley of Wādī Harrīnah (W. Harrine) 10 km south of Al Ḥarf, and 2) the valleys of Wādīs Khayrah and Birkah, 5-10 km north of Al Ḥarf. The widest seasonal fluctuation in plant growth occurs between June 1975 and October 1975. In September 1972 vegetation was scarce.

Wādī al Furdah-Wādī al Jufrah and
Wādī Raghwān (W. al Mukhaynia) Drainage basins

Surface water.--None on any image. All streams in these basins are ephemeral.

Vegetation.--There was no vegetation apparent on images showing the drainage basin of Wādī al Furdah. No vegetation was present in the valley along the lower reaches of Wādī al Jufrah in September 1972, but there was some in September 1973, and in June and November 1975. Plant growth was most vigorous there in October 1975, and vegetation covered a much enlarged area then. Vegetation also occurs in a zone about 10 km by 3 km, east of the gravel terraces which border the valley of Wādī Raghwān (W. al Mukhaynia) on the south slope of the Wādī Jawf region. It was most vigorous in June 1975, less so in October 1975, and had become dormant in February and March 1976. Wide seasonal and yearly variations in plant growth were also detected in the channels of Wādī Jawf, upstream from its junction with Wādī Raghwān, and also in small reaches of Wadi Ḥalḥalān. Likewise, vegetation is prominent in the valley floor of an unnamed wādī south-southwest of the city of Ash Shaliq (Al Chalek). At all these locations, there are large annual and seasonal fluctuations in plant growth. Vegetation there did survive the 1972 drought.

Wādī Adhanah Drainage Basin

Surface water.--The Wādī Adhanah drainage basin is the largest within the Wādī Jawf catchment area. It is underlain by Precambrian crystalline rocks, by Tertiary bedded sedimentary rocks, and by Tertiary and Quaternary volcanic rocks. The only surface water detected outside Wādī Adhanah is in a short wādī that winds across the plain (Qāʿal Fayd) near Ridāʿ, and in a south-bank unnamed tributary to Wādī Adhanah, near $15^{\circ}00'$ N. and $45^{\circ}00'$E. Wādī Adhanah is intermittent for 38 km, from about $15^{\circ}13'$N., and $44^{\circ}59'$E. to the watergap, located 9 km upstream from the city of Maʾrib. Surface flow ceases at the water gap, and the stream, north of the water gap and downstream from the site of the ancient dam built across it, is ephemeral. Seasonal and yearly runoff of Wādī Adhanah varies widely: In September 1972, there was only a trickle of water in two reaches of Wādī Adhanah west of the water gap, each about 2 km long, one just upstream, and the other 9 km southwest from the water gap. Runoff fluctuations in Wādī Adhanah and in Wādī al Khārid are among the most spectacular in the YAR.

Vegetation.--Vegetation grows on the valley floors of many wadis that drain the eastern Precambrian terrain of the YAR, with tremendous variation in plant growth. There was only spot vegetation in these valley floors in February 1976, at a time of low flow, whereas growth was vigorous in long reaches of these same valley floors in October 1975. Plants in irrigated fields near Ridāʿ were growing vigorously in February 1976. Natural vegetation and irrigated fields occur on terraces and the flood plain of the unnamed south-bank tributary to Wādī Adhanah, 10 km upstream from the ancient Maʾrib dam.

Downstream from the dam, natural vegetation and irrigated fields are sporadic along Wādī as Sudd (Wādī Saba), and downstream from Ma'rib along Wādī Abrad. There was no discernible vegetation in September 1972. The most vigorous plant growth in irrigated fields northeast of Ma'rib occurred in June 1975; farther downstream, near the junction of Wādī Abrad and Ad Dabil, most vigorous growth occurred in October 1975. This three-month time lag between vegetation peaks in two distant reaches of the same wādī is worth investigating further, as it might suggest recharge of ground water by streamflow in one reach and ground-water discharge in the other.

Wādī al Khāniq (Wādī Manqai) Drainage Basin

Surface water.--All streams in this basin are ephemeral. Ground water may occur under the channel of Wādī al Khāniq west of Jabal Samaʿ (1990 m).

Vegetation.--Cultivated fields occur only in the upper valley of Wādī al Khāniq, and near the cities of Jadīdah (Al Jadidah), and Al Nedja. Strong seasonal variation in plant growth is indicated: Vegetation observed in June 1975 reached a peak in October 1975, and faded away by February 1976.

Small Unnamed Wādī Drainage Basins Northeast of Jabal Omrikha (1490 m)

Surface water and vegetation.--All streams are ephemeral in these basins, and no vegetation could be identified at any time. Farther north, grass was observed from the air growing in the intervening lowlands between long seifs in June 1975, but could not be detected on Landsat images.

Wādī Ḥarīb Drainage Basin

Surface water.--A trickle of water was identified in the lower courses of Wādī Ablaḩ and Wādī Jirādhah, and channel darkening in some reaches suggested near-surface ground-water underflow in June and October 1975. Annual and seasonal fluctuations are prominent: Some water was present in February 1973, but none in September 1972 and February 1976.

Vegetation.--Vegetation is confined to valley floors, and the alluvial plain of Wādī Jirādhah. Annual and seasonal variations in plant growth are great in the alluvial valley of Wādī Jirādhah, less so in the valleys of other wādīs. Even in February 1976, at a time of low flow, plant growth persisted there in spots.

Wādī Bayḩān Drainage Basin

Surface water.--All streams are ephemeral in this basin, except in a reach of Wādī al Ghayl near the border with the People's Democratic Republic of Yemen and at $14^{\circ}30'$ N, in September 1972 and October 1975. Flows fluctuate seasonally.

Vegetation.--Vegetation is restricted to the valley floors of wādīs. Plant growth is prominent in the valley of Wādī al Ghayl and its upper course tributaries. Variation in plant growth is great. Plant growth was good in September 1972, but there was little vegetation in 1973. Plant growth was vigorous in October 1975, and persisted to a lesser extent until February 1976.

Wādī Markhah Drainage Basin

Surface water.--All streams in this basin are ephemeral with the following exception: There was streamflow in reaches of Wādī Markhah, Wādī Quwah, and Wādī Jumhūrī (W. Gumhuri), along the border with the People's Democratic Republic of Yemen in late June 1975, and also in February 1976. A wide-ranging seasonal and annual fluctuation is indicated by the spectral evidence.

Vegetation.--Vegetation is restricted to the land adjacent to wadis, particularly to the valley floors of Wādī al Qawl, and Wādī Laylān and its tributaries, near the junction of Wādī al Qawl and Wādī Laylān. There is a marked seasonal variation in plant growth: the vigorous growth observed in October 1975 had all but faded away by February 1976.

Red Sea Catchment Area

The Red Sea catchment area is the second largest in the YAR, and it includes the drainage basins of the two largest rivers in the country: Wādī Mawr and Wādī Zabīd. The headwaters and middle courses of all major streams in this catchment area are in the Red Sea escarpment; their lower courses traverse the coastal plain, the Tihāmah, although surface flow generally ceases a long distance from the coast. The drainage basins of all streams, except those of coastal streams, are almost entirely east of a high range of foothills facing the Tihāmah. The shape of many of the drainage basins is strongly controlled by geologic structure (Wādī Mawr), and the stream network may be unusually asymmetric (Wādī Surdūd). Those streams arising in the Red Sea escarpment enter the Tihāmah through a narrow water gap across the high range of foothills, and follow a course incised a few meters below the level of the Tihāmah. From the northern border of YAR with the Kingdom of Saudi Arabia to the entrance of Wādī Mawr onto the Tihāmah, Precambrian metamorphic and granitic rocks predominate in the Red Sea escarpment; from Wādī Mawr south, volcanic rocks predominate.

Colluvium and alluvium, from sand to gravel size, and windblown sand and silt are the Quaternary deposits commonly at or near the surface of the Tihāmah. Lateral hydrologic continuity in these deposits, from the channel of one transverse stream to another, is undetermined.

The streams in the two northernmost basins in the YAR are tributaries to Wadi Difāʿah (W. ad Dafa), Wādī Hanabah, and Wādī Ḏamad. They all flow down the Red Sea escarpment into the Kingdom of Saudi Arabia, and all are ephemeral strears.

Wādī Jīzān (Wādī Qīzān)-Wādī Maʿbār Drainage Basins

Surface water.--Wādī Maʿbār, east of the border with the Kingdom of Saudi Arabia, is a perennial stream in its middle course. Flowing water was detected in it in October 1975, and in September and March 1973. Other streams are ephemeral.

Vegetation.--There is some diffuse vegetation on mountain slopes, and little or none on the valley floors. Plant growth was most extensive in October 1975, but it was also detected in March and September 1973.

Coastal Stream Drainage Basins A

Surface water.--At least four streams flowing into the Kingdom of Saudi Arabia are perennial for short stretches east of the border in the YAR. From north to south, they are: (1) an unnamed south-draining wādī south of Nadhīr (Mt. Nadhir-2300 m); (2) Wādī Khulab; (3) Wādī Liyyah; and (4) Wādī Taʿashshar. Other perennial streams are: Wādī Ḥaraḏ, perennial in its middle course down to the water gap where it debouches into the Tihāmah, 6 km northeast of the city of Ḥaraḍ, and north of Khudhrayn (Mt. Kudharain--320 m); Wādī Ḥayrān, for a short stretch of 2 to 3 km, upstream from its entrance onto the Tihāmah; Wādī Ḥabl, along a southeast-trending reach in the Tihāmah and close to the foothills; Wādī Bawḥal and Wādī al Qūr (W. al Qur) in short stretches, east of the first range of foothills; and Wādī Banī Nāshir and an unnamed wādī south of it, on the Tihāmah close to the foothills.

Vegetation.--Vegetation is sparse in the mountains of the Red Sea escarpment, and denser along the base of the foothills on the Tihāmah and on land adjacent to wādīs on the Tihāmah, including cultivated fields. Some annual variation in plant growth is indicated on the images: Vegetation was denser and more vigorous in October 1975 than in September 1973.

Wādī Mawr Drainage Basin

Surface water.--The Wādī Mawr drainage basin is the largest in the Red Sea catchment area. Except in the headwaters, where all streams are ephemeral, high-order streams and some tributaries are perennial. Wādī Mawr is perennial in a northeast-trending reach which is 16 km long upstream from the junction with Wādī Lāʿah, and possibly intermittent farther upstream. Two east-bank tributaries to Wādī Mawr, Wādī Lāʿah and Wādī Warū (Wādī Ḥusay), are perennial along most of their courses, and a third one, Wādī Dhubāwah-Wādī Sharas, is an intermittent stream. The headwaters of these tributaries to Wādī Mawr are in the vicinity of Jabal Miswar (3240 m), above an altitude of 3,000 meters. In addition, Wādī Lāʿah has four intermittent tributaries: Wādī Samʿ, a south-bank tributary, and farther east, Wādī Rummān (W. Roman), Wādī ʿIyal ʿAlī, and Wādī Ḥijlah. Wādī Mawr is perennial for 25 km of its incised course across the Tihāmah, and yearly fluctuations in runoff and extent of surface flow are common. Wādī Mawr flow in the Tihāmah was 3 km longer in September 1973 than in October 1975, but in August 1972, there was only a thin trickle in this 28-km-long channel.

Vegetation.--Vegetation is lightly scattered throughout the foothills of the Red Sea escarpment. Agriculture is practiced on land adjacent to the channel of Wādī Mawr across the Tihāmah, from the base of the foothills to a distance about two-thirds of the way down to the coast and the city of Al Luḥayyah. Cultivated fields near Wādī Mawr are grouped into two clusters, which assume the shape of two conical sections, with the apex of each cone being oriented toward the foothills. Plant growth was relatively vigorous in September 1973, but was at its best in October 1975, when it approached within 7 km of the Red Sea coast.

Coastal Stream Drainage Basins B

Surface water.--Water was detected in the following wadis during September 1973 and October 1975: From north to south, Wādī ʿAyyān, Wādī ʿUlaysī, Wādī Tabāb, Wādī Ḥaṭab, and Wādī Shebe. Little or no water was present in these wādīs in August 1972.

Vegetation.--Vegetation is dense on Jabal Manābira (850 m), and in the foothills to the south of it. The Tihāmah plain is cultivated along the base of the foothills, and also between Wādī Tabāb and Wādī Shebe. There was no or little vegetation in August 1972 on the Tihāmah, some in September 1973; and plant growth was at its best in October 1975.

Wādī Surdūd Drainage Basin

Surface water.--In October 1975, Wādī Surdūd contained water for 24 km upstream from the water gap, where the stream enters the Tihāmah. Farther upstream, Wādī Surdūd was intermittent in October 1975 and September 1972. Across the Tihāmah, surface flow extended as far as the city of Hardha and the Russian Industrial Farm in September 1973 and October 1975; in August 1972, it hardly extended beyond the water gap near Jibal Dahnah (Jabal Damal-1050 m). Most, perhaps all, tributaries are ephemeral streams.

Vegetation.--There is sparse diffuse vegetation in the mountains. Vegetation also occurs on valley floors, and the upper reaches of the Tihāmah are under general cultivation, especially near the city of Hardha. The state farm, managed by Russian agronomists, is easily recognized as the largest piece of irrigated land on the Tihāmah. It lies along the north bank of Wādī Surdūd, west of Harda. Seasonal variation in plant growth is easily recognized in the farmed areas. There are also large annual fluctuations in plant growth with little vegetation in September 1972, more in September 1973; plant growth was at its best in October 1975.

Coastal Stream Drainage Basins C

Surface water.--Water was detected in an unnamed incised wādī, winding around the north end of Jabal Adh Dhāmir (1100 m) located approximately 6 km northeast of Bājil, in a stretch extending for 6 km east of Jabal Adh Dhāmir (1100 m). Water was present there in October and September 1975, and September 1973, but not in August 1972. In an unnamed wādī south of Jibal

Dahnah (1050 m) there was water close to the surface in October 1975 and September 1973, but none in August 1972.

Vegetation.--Vegetation is most prominent in the upper Tihāmah, cultivated fields extending from the base of the foothills to the banks of wādīs, on valley floors, and on the Tihāmah plains, northwest of the city of Bājil. The two state farms, managed by German agronomists, were not identified like the Russian industrial farm had been through their irrigated orchards and crops. They are located near the road junction between the road to Mocha, and the Al Ḩudaydah-Sana highway. The yearly fluctuations in plant growth follow the same temporal pattern recognized elsewhere in the YAR with little or no vegetation in August 1972, more in September 1973, and the most vigorous growth having occurred in October 1975.

Wādī Sihām Drainage Basin

Surface water.--Water was detected in Wādī Sihām in its course through the mountains of the Red Sea escarpment and also across the Tihamah. Yearly change in runoff is appreciable, but there was still water in Wādī Sihām in September 1972. Seasonal fluctuations appear more wide ranging than yearly fluctuations: There was little water in Wādī Siham in June 1975.

Vegetation.--Most of the diffuse vegetation in the mountains is on Jabal Buraʿ (2270 m), close to the Tihāmah. Vegetation on the Tihāmah is light. Seasonal increase in plant growth between June and October 1975 was great.

Coastal Stream Drainage Basins D

Surface water.--There was water in an unnamed wādī only in September 1973. All streams in this region probably are ephemeral.

Vegetation.--The foothills east of the Tihāmah are the most densely vegetated part of the Red Sea escarpment. Growth of vegetation on the Tihāmah is also vigorous. A large seasonal change is indicated by the spectral data.

Wādī Rimaʿ Drainage Basin

Surface water.--In the mountains of the Red Sea escarpment, Wādī Rimaʿ is alternately a losing and gaining stream. It carried water in October 1975, and also in September 1973. There was little water in the course of Wādī Rimaʿ across the Tihāmah in September 1972, and none in June 1975. Wide annual and seasonal fluctuations in runoff are indicated.

Vegetation.--Vegetation is diffuse on mountain slopes and mountain peaks of the Red Sea escarpment; plants also grow on the alluvial plains, and on the Tihāmah, especially on land adjacent to Wādī Rimaʿ, where the stream enters the Tihāmah. Seasonal and annual fluctuations in vegetative cover are evident.

Wādī Zabīd Drainage Basin

Surface water.--Wādī Zabīd is the second largest drainage basin in the Red Sea escarpment. After Wādī Mawr and its tributaries, Wādī Zabīd and its network of tributaries have the longest (extent) of perennial streams. In October 1975, water was flowing in Wādī Zabīd, both in the mountains of the Red Sea escarpment and in the Tiḥāma, in Wādī Ḫammān and in Wādī Annah. There was also water in the headwaters of two tributaries to Wādī Suhul, north of the city of Ibb. In September 1972, Wādī Zabīd had become intermittent along some stretches.

Vegetation.--Diffuse vegetation occurs mostly on mountain slopes and wide valley floors, northwest of the city of Ibb. Tree growth and cultivated fields are typical of this region. Diffuse vegetation also occurs in the mountains northeast of the city of Zabīd. On the Tihāmah, plant growth is vigorous on alluvial fans and on land adjacent to wādī channels. Little vegetation grows on the narrow valley floors of most wādīs. Some yearly and seasonal change in plant growth on the Tihāmah is indicated.

Coastal Stream Drainage Basins E

Surface water.--Water was detected in Wādī al Fawwahʿhāh, and in unnamed tributaries to the north, both in mountain valleys and across the Tihāmah in October 1975. Less water was present in September 1973, and none in June 1975. There are large annual and seasonal fluctuations in runoff.

Vegetation.--Plant growth is vigorous on the valley floors of most wādīs, and extremely vigorous on alluvial cones at the base of the foothills in the upper part of the Tihāmah. There was little vegetation in September 1972 and 1973, some in June 1975, but plant growth was abundant in October 1975.

Coastal Stream Drainage Basins F

Surface water.--As in the basins just described, there are large annual and seasonal fluctuations in stream runoff. In October 1975, there was water in the course of Wādī Nakhlān through the mountains and across the alluvial plain at the head of the Tihāmah. The same condition applied to Wādī Suwayhirah. Water was detected also in September 1973, there was none in June 1975.

Vegetation.--There is diffuse vegetation in the mountains north of Wādī Nakhlān. Plant growth in cultivated fields is vigorous on the flood plains of two unnamed wādīs, near Ḥays in the upper part of the Tihāmah. Seasonal change in plant growth is indicated and there was little vegetation on the flood plains and valley floor in September 1972, September 1973, and in June 1975 as compared to more abundant plant growth in October 1975.

Coastal Stream Drainage Basins G

Surface water.--All streams in this basin are ephemeral.

Vegetation.--There is diffuse vegetation in the foothills, and some cultivation on land adjacent to wādī channels, and on alluvial cones at the base of the foothills. Little vegetation was detected prior to October 1975.

Wādī al Ghayl-Wādī Rasyān Drainage Basins

Surface water.--Water was detected in Wādī Rasyān in March 1973, September 1973, and also in September 1972. Wādī Rasyān terminates in the Tihāmah. In March 1973, there was water only in the channel of Wādī Rasyān, which extends across the Tihāmah. In September 1972 and in October 1975, water was detected in the upper channels of Wādī Tānif. In November 1975, and in September 1972, there was water in the lower course of Wādī Maksab and Wādī al Ghayl (Wādī al Kabir) (Plate 1B), upstream from their junction which terminates in the Tihāmah. In March 1973, there was little water in Wādī al Ghayl and Wādī Maksab, little or none in Wādī al Ghayl upstream. Seasonal and yearly fluctuations in these wādīs are more restricted than farther north in the Red Sea catchment area.

Vegetation.--Diffuse vegetation is plentiful on Jibal Ṣabir (3006 m), particularly on its western slopes, and on the mountains to the west of it. Plants, mostly cultivated fields and orchards, grow at the upper and lower ends of the valley floors of Wādī Kaleyba, and in the upper part of the valley of Wādī al Ghayl. Except in the valleys of these two wādīs, seasonal and yearly fluctuations in plant growth are not obvious.

Coastal Stream Drainage Basins H

All streams in this region are ephemeral, and vegetation is very scant in these basins.

Gulf of Aden Catchment Area

The Gulf of Aden catchment area receives the greatest amount of precipitation in the YAR. Surface water was detected in four of the five drainage basins in the area. Yearly and seasonal fluctuations in seasonal flow do occur, but are not as marked as in the other three catchment areas of the country. Most streams are ephemeral.

Wādī Ḥamrā', Wādī Ḥarīb, and Saylat Sīḥ Drainage Basins

Surface water.--Some water was present in the headwaters of Wādī Yahir (W. Yislam), and possibly in Wādī Zaydān in October 1975, and a lesser amount in September 1972 and February 1976. No water could be detected in those streams in February 1973 or in June 1975.

Vegetation.--Vegetation is confined to the valley floors of Wādī Ḩamrā; north of Rahwah (Rahwat), and of Wādī Yahir (W. Yislam), and possibly Wādī Zaydān in their upper reaches. The presence of vegetation in September 1972 and October 1975, and its absence in February 1973 and June 1975 indicate wide seasonal variations in plant growth.

Wādī Banā Drainage Basin

Surface water.--The Wādī Banā drainage basin receives the greatest amount of precipitation in the entire country (figure 4). In October 1975 and September 1973, there was water in the headwaters of Wādī Banā, and also southeast of its junction with Wādī Ajlub. Water could also be detected in the headwaters of two north-bank tributaries to Wādī Banā, northeast of Damt. Wādī Ajlub is an intermittent interrupted stream, northwest of its junction with Wādī Banā. Seasonal and annual fluctuations in surface flow occur. Little, if any surface water could be detected in June 1975, and it probably occurred only in pools between dry reaches in September 1972. Al Ḩaradah, has a thermal spring, issuing from a mound of tufa and travertine. It is the largest of several mound springs near the city of Damt and can be identified definitely on the Landsat image taken in October 1975.

Vegetation.--Vegetation in the basin of Wādī Banā occurs in the narrow valley floors of Wādī Ajlub, and in the valleys of the tributaries to Wādī Banā mentioned in the previous paragraph. It also occurs more diffusely on mountain slopes, south of the upper course of Wādī Banā, and north of its lower course. There is little or no apparent change in plant growth or valley floors, but some seasonal and yearly fluctuations in the vegetation growing diffusedly on mountain slopes were detected on the Landsat images analyzed.

Wādī Tuban Drainage Basin

The lower part of this drainage basin is outside the YAR. Only the headwaters of Wādī Tuban, herein referred as the Upper drainage basin, and the upper course of its west-bank tributaries are within the YAR. They are described separately below.

Upper drainage basin surface water.--Salabat as Sayydah is an intermittent stream, probably gaining and losing water for 15 km downstream and southeast of the city of Ibb. Streamflow also was in an unnamed tributary southeast of Jabal Bārid (2500 m) in October 1975, and also in September 1972 and 1973. Seasonal and yearly fluctuations in streamflow are not obvious on existing images.

Upper drainage basin vegetation.--Vegetation grows in the valley floors of wādīs, but the dip slopes west of Ibb are lightly forested. The mountain range north of Ibb, and the slopes of Jabal Khaḏrā', 2600 m 10 km south of it, also are forested, but more lightly. Seasonal and yearly changes in plant growth are not evident.

West-bank tributary drainage basin surface water.--Streamflow was detected in Wādī Dhī Sufāl (Wadi Ẕubā), south of the village of Dhī Sufāl, in Wādī Nakhlān and in Wādī Amid, downstream from its junction with Wādī Nakhlān in October 1975, and in September 1972 and 1973. Streamflow in shorter reaches in June 1975 suggested seasonal fluctuation.

West-bank tributary drainage basin vegetation.--Vegetation grows in the valleys of Wādī Saram, Wādī Warazān, Wādī Khadir, Wādī Dahr, Wādī Dabbah and Wādī Shamera, 5 km southeast of the town of Māwiyah and Jabal Amā'imah (2230 m). Vegetation also occurs on the steep valley slopes and the valley floor of Wādī Amid. Except in the northern part of the basins, plant growth was most vigorous in September 1972, less so in March 1973 and November 1975. Some seasonal change is indicated. Plants grow on the valley floors of Wādī Tis'ān and its main tributaries, but seasonal and yearly variation is not obvious.

Gulf of Aden Coastal Stream Drainage Basins

Surface water.--All streams in these drainage basins are ephemeral.

Vegetation.--Vegetation is diffuse on the high plain near At Turbah. Otherwise, plant growth is confined to very narrow valley floors of Wādī Fawān, Wādī 'Ukayyān southwest of At Turbah, and Wādī al Adīr and Ghayl Dabāb, about 18 km east of At Turbah. Plant growth reached a peak in September 1972, but was less vigorous in March 1973 and November 1975.

CONCLUSIONS

The following conclusions concerning the occurrence of surface and ground water in the Yemen Arab Republic may be made from the analysis of selected Landsat images:

Landsat imagery can be used to delineate large regional drainage areas, and to map the boundaries between major drainage basins (pl. 1).

Periodically repetitive Landsat imagery can be used tentatively to identify ephemeral, intermittent, and perennial streams, determine where streamflow starts and ceases, and transfer this information to existing topographic maps or mosaics of Landsat images (pl. 1). Most streams in the YAR are ephemeral streams.

The repetitive Landsat image coverage available provide a graphic illustration of the seasonal and yearly fluctuations in streamflow to be expected in the arid and semi-arid regions of the YAR. The seasonal rainfall pattern varies from one region to another in the Yemen Arab Republic, thus, not only storm runoff but also spring-fed streamflow occurs at different times in different regions of the YAR.

Streamflow is greatest (in terms of both wet channel length, and color value on a Landsat image false-color composite) in the summer and early fall of each year, and the low flow of perennial streams (evaluated in the same terms) occurs in late winter or early spring.

The available imagery for Rub' al Khali and Wādī Jawf valley and the northern half of the Red Sea catchment area suggests that the lower the annual precipitation, the greater the seasonal and annual fluctuations in stream runoff. Conversely, fluctuations in stream runoff, and also variations in the vigor of plant growth are smaller and less obvious in the Gulf of Aden catchment area and in the southern part of the Red Sea catchment area, where annual precipitation is relatively high.

There is a direct relationship between total length of perennial stream reaches in a drainage basin and basin area; also, the higher the elevation of headwaters, the greater the number of small-order tributaries. In this respect, the drainage basins of Wādī Mawr and Wādī Zabīd in the Red Sea catchment area, and those of Wādī Tuban and Wādī Banā in the Gulf of Aden catchment area may be said to hold the largest surface- and ground-water resources in the country.

Streamflow in the lowest reach of any stream in the Wādī Jawf and Red Sea catchment areas contributes to the recharge of the ground water in valley and coastal plain alluvium or, at least, is diverted into canals to replenish soil moisture. However, the percentage of these contributions as against water loss through evaporation is likely to be low.

The lower valleys of Wādī al Khārid and Wādī Adhanah in the Wadi Jawf catchment area, and to a lesser extent those of Wādī Ḩaraḑ in the Red Sea catchment area appear under-developed. Irrigation farming downstream from where streamflow ceases in the lower valleys of these streams is at a minimum, perhaps because diverted streamflow is insufficient to replenish soil moisture.

RECOMMENDATIONS

This country-wide survey of the hydrologic features of the YAR has resulted in tentatively identifying perennial and intermittent reaches, and areas where soil moisture is available for plant growth or where the water table is at a shallow depth. This new information greatly expands what is known of the hydrology of the YAR, especially the surface-water hydrology. Even when accurately known, however, the occurrence of surface and ground water, by itself, hardly constitutes an adequate basis for hydrological forecasting and sound management of water resources. The listed recommendations for future hydrological investigations in the YAR are made after considering the need for institutional innovation, and a sound methodological approach to network design; site selection; data collection, processing and analysis; forecasting; and logistical support. Some studies and investigations are recommended.

Institutional Recommendations

1. The Landsat imagery program should be continued and expanded to cover the whole country at least once a month for several years. The expanded and more frequent coverage is needed to monitor the change in water occurrence and to verify the extent of plant growth. The imagery will also permit periodic inventories of agricultural land use.

2. An effective country-wide program of surface and ground water hydrological studies should be initiated to meet the present and future needs of the YAR for irrigation, rural, livestock, and municipal supplies in the short term, and of industry in a longer-range program. From the regional reconnaissance framework provided by the imagery system of an orbiting spacecraft, which was adopted in the present report, the program should evolve toward qualitative and quantitative studies in the hydrological and ecological fields, utilizing direct and indirect methods. These studies may be site-specific or regional in scope, but the more localized ones need to be put within the broad regional framework dealt with in first-priority investigations.

3. Permanent country-wide networks for gaging streams and for measuring water levels in wells should be initiated. In organizing these networks and locating gaging stations and observation wells, prime consideration should be given to the hydrological and agricultural evidence shown on Landsat images, as described in this report.

4. Topical studies should be undertaken to observe and analyze sheet flood processes. Our brief ground reconnaissance of the YAR in June-July 1975 showed that sheet floods are of common occurrence and uncommon magnitude in the YAR, and that they occur on steep mountain slopes as well as on gentler valley slopes. Vast amounts of weathered rock debris, particularly in the silt-size range are transported during sheet flooding, and traditionally have been trapped by Yemeni farmers in their irrigation terraces, possibly as means of periodically building, adding to, or renewing, their soil resources. One study in sedimentology particularly applicable to the building of dams and their life expectancy in the YAR should deal with the ratio between the sediment loads in overland flow and stream channels.

5. Expansion of the present meteorological network is recommended, to include at least one weather station per major vegetation zone in each one of the drainage basins. Air temperature should be monitored, so that ground-water temperature can be related to its mean annual value. Latitudinal variation of the frost line in the mountains needs investigation, as freezing in winter affects streamflow and discharge of ground water to springs and seeps. Rain gauges should be equipped with automatic recording equipment so that each one of the 20 or 30 showers annually can be

quantified, and so that the extent of the rainy seasons can be determined accurately.

Only in this way can the probability of storm runoff and flood occurrence in a given drainage basin or part of it be determined. In the YAR, sheet wash and overland flow are modified by either natural or man-made ponding, evaporation, and replenishment of soil moisture by diversion. These modifications are important aspects of the hydrologic regimen in the YAR. Because of them, the occurrence of storm runoff in stream channels, and recharge to the water table, probably are even more erratic events than the occurrence of rain storms, and cannot be predicted from the knowledge of storm frequency distribution alone. Not only should observations be made to calculate by direct or indirect means the annual runoff of major streams, but methods should be devised to quantify the amount of surface water, particularly overland flow, which is put to agricultural use <u>before</u> it reaches stream channels. For planning purposes, there is the further need to relate storm event frequency and magnitude within each one of the two rainy seasons, and also to find out whether there is a second period of base flow in perennial reaches during the short intervening period between the two annual rainy seasons.

Floods and drought are hazards familiar to hydrologists and planners. The intricate pattern of irrigation terraces, which is a striking feature of the Yemeni landscape, represents community efforts to control floods and overland flow which were initiated thousands of years ago. The ruins of the Ma'rib dam on Wādī Adhanah in the eastern part of the YAR are a reminder of ancient successful efforts at flood control and irrigation farming. On the other hand, Yemeni agriculture seems as vulnerable to drought as it has ever been.

The recent regional drought, which affected the north tropical zone (including the YAR) for a period of several years, suggests a climatic (not necessarily periodic) cycle, the duration of which remains to be determined. As described earlier in this report, the effects of this drought on the environment are well documented on August-September 1972 Landsat-1 images of the YAR, and also in 1973. The Landsat-1 evidence shows that these effects were widespread and not restricted to the valleys of the main wādīs. Besides reducing the length of perennial and intermittent reaches in streams, drought reduced plant growth throughout the YAR. It provides overwhelming and indisputable evidence that in the YAR the fluctuations in length of the perennial and intermittent reaches of streams, together with fluctuating ground-water levels, may provide data which can be used as sensitive indicators of the climatic threshold below which human settlement in the YAR is impaired.

It is not clear how hydrologic investigations aimed at evaluating maximum floods and annual runoff in some wādīs of the YAR will improve country-wide flood-control practices, nor how water stored in surface reservoirs can be beneficial to agriculture in lands adjacent to the Red Sea, where the annual potential evaporation is reported to approximate 2 meters. On the other hand, an intensive study of the hydrologic regimens of perennial and intermittent reaches of streams in the YAR, monitoring of water levels in water wells, and ecological investigations aimed at continuous monitoring of plant growth will provide basic data, which should be of considerable value for regional country-wide planning.

Methodological Recommendations

1. Network design: To the extent possible, location of gaging stations and observation wells, as well as the selection of equipment and methods, should have multi-purpose objectives, so that measured or calculated surface-water data may be of maximum use to an analysis of ground-water hydrology, and vice versa. The adoption of this recommendation is one of the conditions required for an effective, all encompassing hydrological program, particularly in a country where satellite data show that both effluent and influent streams are commonplace.

2. Site selection: Sites for gaging stations and observation wells should be selected with consideration for the following factors:

a) The spatial distribution of rain storms in the YAR largely depends on the ratio between the dimensions of the storm and the area affected by it on one hand, and the size of the region being studied on the other. One meteorological and ecologic problem along the Red Sea escarpment concerns orographic control of precipitation. Along the Red Sea escarpment (the mountain front just east of the Tihāmah), wide seasonal and yearly variations in plant growth are detected on some slopes, whereas little variation occurs on nearby slopes of the same orientation. Further studies may well show that greater vigor in plant growth on some slopes is not due to greater retention of soil moisture because of favorable rock types and joint pattern, but rather that these mountain slopes lie across the tracks of major regional storms.

b) Measurement of the runoff of a drainage basin may give quantitative meaning to the perennial and intermittent reaches identified on Landsat images.

c) The influence of the major rock types in the YAR (alluvium, colluvium, granitic and metamorphic rocks, carbonates, sandstone, and volcanic rocks) on streamflow, sediment load, ground-water storage, recharge and discharge, and quality of water is poorly known. A large area in the Yemen highlands north of Sana is underlain by the Amran (Jam) limestone of Jurassic age; yet large-scale karst topography is either poorly developed or not obvious in the field. Why not? A chemical analysis of samples of Amran (Jam) limestone to determine its dolomite content, and measurement of the percentage of solids actually dissolved in surface and ground water originating in this area may help solve this hydrologic, geomorphologic and possibly climatic riddle. Likewise, the storage characteristics and permeability of the Yemen volcanics require study.

3. Data Collection: Perennial and intermittent streams should be mapped on Landsat images enlarged to an appropriate working scale, and the information should be transferred to existing topographic maps at 1:250,000 scale.

Collection of some hydrologic data should be timed to coincide with low flow (ideally base flow) and flood stages in streams. In this way, it may be possible to relate and compare specific image data with quantitative hydrologic data; to determine the occurrence of a stage of summer low flow that might eventually be identified spatially on Landsat images, and eventuallv to make long-term low-flow forecasts for the YAR.

Forecasting

Some redundancy should be built into the methods employed in the measurement or calculation of hydrological data. In no way should the general approach to surface- and ground-water investigations in the YAR be confined to only one method of hydrological forecasting. Conventional hydrological and meteorological observations must be made concurrently with indirect methods in which stream hydraulics are related to channel geometry. Over the years, only an adequate data base will substantiate or negate the validity of the results obtained by the mathematical-statistical approach to stream dynamics. Further, some of the other methods employed in hydrological forecasting, particularly those used to calculate evapotranspiration rates, should also be considered in the formulation of an overall water resources program in the YAR (World Meteorological Organization, 1975, p. 5).

Logistical Support

In the selection of sites for gaging stations and observation wells, the type of logistic support the field hydrologist will get in servicing stations and monitoring wells should receive priority attention. Similarly, in determining the optimal frequency of observations, accessibility and availability of trained technicians should be the overriding factors, rather than a limitation based on the general level of economic development in the country. At the present time, the YAR is characterized by a scarcity of good roads, and a surplus of untrained but high-salaried technical labor. In any case, sandy wastes, lack of population, tremendous topographic relief (2,500 meters over a 10 to 20 km belt in the Red Sea escarpment), valley dissection, and terraced irrigation farming will limit easy access by road to many regions in the foreseeable future.

We recommend that the sites of gaging stations and observation wells be selected with the understanding that both be serviced from a helicopter, where and when required, and therefore that space be allotted for a landing site near some or perhaps most gaging stations and observation wells. In addition, helicopter service, with or without a simple radio alert network, will make it possible to perform <u>occasional</u> as well as regular monitoring of hydrological processes and meteorological phenomena. Flash floods, flows in ephemeral streams, torrential downpours accompanied by sheet wash and tremendous rates of erosion, sediment transport and deposition, then, can be monitored on an emergency basis. In turn, any one of these monitored events takes on added meaning, if its effects on the ground can be identified on Landsat images. Water is the most valuable mineral in the agricultural economy of the YAR, and the cost of using and maintaining a helicopter for hydrologic field work, where required, may be fully justified in terms of countrywide benefits returned, or when used jointly with a geological survey of the country.

Recommendations For Further Studies

1. Expansion of the present remote-sensing program to include routine acquisition and analysis of weather satellite images, so that regular precipitation data collected at weather stations can be related to nephanalysis.

2. Determination of theoretical and actual evaporation rates in each one of the four catchment areas, possibly by taking advantage of the thermal data routinely acquired in the thermal infrared band of existing weather satellites.

3. A quantitative evaluation of the consumptive use of water by plants in at least one of the major drainage basins. In the YAR, natural soil moisture is replenished and augmented by diverted overland flow, streamflow, and water from wells. The proportions of these sources of water for agricultural crops should be estimated, so that their relative importance in the national economy can be known. Total acreage under cultivation and in light forest can be derived from Landsat images, using computer compatible tapes and existing land-use computer programs.

4. Collection of other types of data needed to interpret Landsat images in greater detail than at present:

a) Data on natural plant cover, and types of crops grown in irrigated and nonirrigated fields. In this context, pollen traps in the vicinity of each of the gaging stations and some of the observation wells should be set up to monitor the pollen rain, and serviced at least one a year. This recommendation recognizes that subsistence agriculture has assured human survival in the YAR for thousands of years, and still is the mainstay of the Yemeni economy. The present pollen rain, therefore, can be used as data base against which past and present changes in natural vegetation and cultivated plants growing in the YAR can be estimated. In turn, changes in plant distribution through time may be useful to infer cyclic rainfall fluctuations, and therefore short-term and long-term climatic change in the YAR.

b) Data on distribution of soil types.

5. Future analysis of repetitive Landsat coverage to outline basins or areas where withdrawal of water exceeds replenishment from all combined sources as evidenced by diminishing vegetated acreage; to map wet lands where brackish water is known to occur at shallow depth, as under the sebkahs that dot the coastal areas along the Red Sea or down valley from irrigated farms where drainage is ineffective; to map the areal extent of coral reefs along the coast as an aid to navigation and fisheries; to map pollution of sea water along the coast. This specialized use of Landsat imagery shows that in a later phase of a country-wide hydrological program, remote sensing of the YAR may be a powerful tool, first in modernizing, and later in enforcing current water laws, once current riparian practices and customs, as well as local ground-water law, are embodied by legislation into a modern unified system of laws.

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APPENDIX I

Glossary of Selected Terms Used In This Report

Ground-Water and Surface-Water Terms

(Definitions are summarized from Meinzer (1923, p. 54-57), and from Langbein and Iseri (1960).)

Ground-water terms--

Ground water: Water in the ground that is in the zone of saturation, from which wells, springs, and ground-water runoff are supplied.

Ground-water outflow (underflow): That part of the discharge from a drainage basin that occurs through the ground water, and that is not measured at a gaging station.

Ground-water runoff: That part of ground water which has been discharged into a stream channel as spring or seepage water.

Mound spring: One which may be produced wholly or in part by the precipitation of mineral matter from the spring water.

Thermal spring: One having water at a temperature appreciably above the mean annual temperature of the atmosphere in the vicinity of the spring.

Surface-water terms--

Base runoff: Streamflow composed largely or wholly of effluent ground water.

Temporal classification of runoff--

Direct runoff: Overland flow entering stream channels shortly after a rainfall.

Discharge: The actual flow of a stream, whether or not subject to regulation or underflow.

Drainage divide: The rim of a drainage basin.

Overland flow: The flow of rainwater over the land surface toward stream channels.

Definition of runoff with respect to source--

Surface runoff: That part of rainwater that appears in streams.

Stream: Water flowing in a natural channel.

Relation to time:

Perennial stream: One which flows continuously.

Intermittent or seasonal stream: One which flows only at certain times of the year when it receives water from springs or from some surface source such as melting snow in mountainous areas.

Ephemeral streams: One that flows only in direct response to precipitation, and whose channel is at all times above the water table.

Relation to space:

Continuous stream: One that does not have interruptions in space.

Interrupted stream: One which contains alternating reaches that are either perennial, intermittent, or ephemeral.

Relation to ground water:

Gaining (effluent) stream: A stream or reach of a stream that receives water from the zone of saturation. It is said to be effluent with respect to ground water.

Losing (influent) stream: A stream or reach of a stream that contributes water to the zone of saturation. It is said to be influent with respect to ground water.

Streamflow: The discharge that occurs in a natural channel, whether flow is diverted, regulated or not.

Underflow: The downstream flow of water through the permeable deposits that underlie a stream.

Vegetation Terms

Plants are grouped into three ecologic classes according to the relative wetness or dryness of their habitats: hydrophytes, xerophytes, and mesophytes (Warming, 1895); they grow in wet, dry, and moist habitats respectively (Daubenmire, 1962, p. 138.)

Plants also have been classified in a way that expresses the relationship of roots to the water table by Meinzer (1923, 1927), and Robinson (1958). Phreatophytes, a term proposed by Meinzer in 1923, are plants requiring large quantities of water for growth; they habitually transpire water either directly from the zone of saturation or through the capillary fringe, whereas xerophytes are plants whose roots are well above the capillary fringe, and therefore transpire soil water only. Mesophytes neither grow in water nor endure prolonged drought.

Phreatophytes, which are indicative of a relatively shallow water table and therefore are of particular interest in this study, are either natural or domesticated plants. Tamarisk (*Tamarix gallica*), a tree growing in wild clumps along the banks of many wādīs in the Yemen, was frequently observed by the writers. On the other hand, alfalfa, widely cultivated in the Yemen in fields irrigated with surface water or ground water, also is a phreatophyte with long-root penetration (Robinson, 1958, p. 600).

Halophytes are plants having a large tolerance for salt and alkali in the soil water; they generally are xerophytes, whose inward zonation by species around the outer fringe of a playa or a natural sump at the end of a losing stream, for example, occurs according to increasing salt tolerance of each species. On the other hand, mangroves, which are a familiar sight along some stretches of the Red Sea landscape, are rooted on the seafloor in the intertidal zone, and therefore answer to the definition of a hydrophyte.

Consumptive use: The quantity of water absorbed by the crops and transpired or used directly in the building of plant tissue together with that evaporated from natural vegetation and cropped areas.

Geologic Terms

(from Gary and others, eds., 1972)

Catchment area: As used in this report one of the four large regional drainage areas toward the Rubʿal Khali, the Arabian Sea, the Gulf of Aden and the Red Sea. Each catchment area includes many smaller individual drainage or river basins.

Escarpment: A long, more or less continuous cliff or relatively steep slope facing in one general direction, breaking the general continuity of the land by separating two levels of gently sloping surfaces, and produced by erosion or by faulting.

Facies: A term used to refer to a distinguished part or parts of a single entity, differing from other parts in some general aspect; for example, any two or more significantly different parts of a recognized body of rock or stratigraphic unit, distinguished from other parts of the same rock or unit by appearance or composition.

Felsic rock: Igneous rock having light-colored minerals in its mode. It is the opposite of mafic rock.

Mafic rock: Igneous rock composed chiefly of one or more ferromagnesian, dark-colored minerals in its mode.

Massif: A massive topographic and structural feature in an orogenic belt, commonly formed of rocks more rigid than those of its surroundings. These rocks may be protruding bodies of basement rocks, consolidated during earlier orogenies, or younger plutonic bodies.

Metasedimentary: A metamorphic rock of sedimentary origin.

Metavolcanic: A metamorphic rock of volcanic origin.

Piercement dome (diapir): A dome where the overlying rocks have been ruptured by the squeezing out of the plastic core material.

Remote Sensing Terms

(from Reeves and others, eds., 1975; and Sabins, 1978)

Band: A wavelength interval in the electromagnetic spectrum; also the spectral image taken in that particular wavelength interval.

Band ratioing: An image can be produced by processing digital multi-spectral data. In ratioing, the value for each pixel of one band is divided by that of another. The resulting digital values are displayed as an image.

Computer enhancement: The process whereby a computer alters the appearance (or contrast) of an image so that the interpreter can extract more information. Enhancement may be done by digital or photographic methods.

Dielectric constant: Electrical property of matter that influences radar returns.

False-color composite: A color image prepared by superposing black and white images of individual spectral bands of the same scene, using different color filters for each band. To produce a Landsat false-color composite, which approximates a color infra-red (or false-color) photograph, a blue filter is assigned to band 4, a green one to band 5, and a red one to band 6 or 7.

Image: The prepresentation of a scene as recorded by a remote-sensing system. Image is a general term, but it is commonly restricted to representations acquired by non-photographic methods.

Mosaic: An image or photograph made by piecing together individual images or photographs covering adjacent areas.

Multispectral scanners: A scanner system that simultaneously acquires images in various wavelength regions of the same scene.

Near-infrared: The shorter wavelengths of the infrared region extending from about 0.7μm to 1.3μm. The term emphasizes the solar radiation reflected from plant materials, which peaks around 0.85 μm and can be recorded by photographic means as well as multi-spectral scanners.

Orbital track: Path of spacecraft travel.

Pixel: A contraction of picture element. In a digitized image, this is the area on the ground represented by each digital value. Because the analog signal from the detector of a scanner may be sampled at any desired interval, the picture element may be smaller than the ground resolution cell of the detector.

Radar imagery: Image obtained through the use of radar, acronym for radio detection and ranging, an active form of remote sensing that operates at wavelengths ranging from 1 mm to 1 m.

Resolution: The ability to distinguish closely spaced objects on an image or photograph.

Scene: The area on the ground, sometime called footprint, that is covered by an image or photograph.

Spectral band: An interval in the electromagnetic spectrum defined by two wavelengths, frequencies, or wave numbers.

Spectral reflectance: The reflectance of electromagnetic energy at specified wavelength intervals.

Sun-synchronous orbit: An earth satellite orbit, in which the orbital plane is near polar and the altitude such that the satellite passes over all places on earth having the same latitude twice daily at the same local sun time.

Swath: That portion of the earth surface scanned in a cross-orbital track direction. The multispectral scanners (MSS) aboard the Landsat spacecraft scan a swath 185-km long, imaging six scan lines in each of the four spectral bands simultaneously.

Thematic mapping: Any photograph or image contains data pertaining to a variety of themes: land, water, vegetation, rock types, land use and many others. In thematic mapping, image data are extracted selectively one theme at a time, and re-imaged separately so as to produce the equivalent of a vegetation map, geologic map, land use maps and other thematic maps.

Thermal infrared: That portion of the infrared region--from approximately 3 to 14 μm that corresponds to heat radiation. This spectral region spans the radiant power peak of the earth.

APPENDIX II

Names of Topographic Maps at the 1:250 000 Scale Covering the YAR

The following is a list of geographic maps prepared for the Yemen Arab Republic by the Director of Military Survey, Ministry of Defence, United Kingdom, 1974, at the scale of 1:250 000. The sheet numbers are those used in the names glossary.

		Coordinates of sheet boundaries (in degrees and minutes)			
Sheet No.	Sheet Name	West	East	North	South
1	Ṣaʿdah	42 40	44 00	17 45	16 00
2	Al Ḥasm	44 00	45 30	17 45	16 00
3	Rayyān	45 30	47 00	17 45	16 00
4	Ḥudaydah	42 40	44 00	16 00	14 15
5	Ṣanʿāʾ	44 00	45 30	16 00	14 15
6	Ḥarīb	45 30	47 00	16 00	14 15
7	Taʿizz	43 00	44 30	14 15	12 30
8	Qaʿtabah	44 30	46 00	14 15	12 30

APPENDIX III

Gazetteer

Published sources listing Yemen Arab Republic place names in the original Arabic are few but complete. The BGN report names used in this report conform to the approved standard names of the United States Board on Geographic Names (BGN), Official Standard Names Gazetteer, Yemen Arab Republic, 1976.

As far as possible, Arabic names in the gazetteer have been romanized from Arabic script according to the transliteration system used jointly by the BGN and the Permanent Committee on Geographical Names (PCGN) for British Official Use (the BGN/PCGN 1956 System as revised in 1972).

Original report names (source names) were former BGN names. The current names are the same as or are similar to these former names.

Orthography--Form and Use

BGN names used in this report are approved standard names. Approved standard names include Long form names and Conventional form names. Long-form name use is preferred here because of the similarity of several original source names. Conventional-form use is preferred by BGN. The native name is used, followed by the Conventional form in parenthesis. Use of the native name is optional; its use here retains an identification and correlation with usage in previous reports.

Additionally some names used are categorized as: Not verified names; these comprise Not verified names and Edited names. Not verified names are used here to retain the sense of geographic location for report purposes. Edited names are names applied to hydrologic and topographic (physiographic) features for report purposes. These names are source names converted to the BGN names with a descriptive ending (not verified).

Refer to names glossary explanation for samples of these name forms and how they are shown.

Names Glossary Information

The names glossary is arranged in four columns, 1-BGN (report) name, 2-Feature description, 3-Coordinates, 4-Sheet number.

The BGN name column comprises report names (source names) used in the original report. Following these names in parenthesis, as needed, are indications of conventional form designation (conv.), native Arabic spellings, and letters indicating that the named feature extends into adjacent country(s) or is located in another country(s). See explanation following.

The feature description column has abbreviations indicating geographic categories; explanation follows.

Coordinates are given to the nearest degree and minute and used for location purpose only. Coordinates apply to, 1-center or near midpoint of region or area, 2-highest point of mountain(s) and hill(s), 3-the mouth of a drainage feature or its junction with another feature.

The sheet number column indicates the quadrangle on which the BGN (report) name is located (see Appendix II). This number allows the reader to locate this name on the correct quad for additional geographic information.

Names Glossary Explanation

BGN (Report) name	BGN name form
1-Al Bayḍāʾ	Approved standard form name
2-<u>Kamaran</u> Island (Conv.) (Kamarān) (Arabic)	Long form name (the complete name)
3-Kamarān	Short form name (as underlined above)
4-Asir (conv.) (ʿAsīr) (Arabic)	Conventional form name (use of the native name in parenthesis is optional)
5-*Ad Dabil	Not verified form
6-ʿAmrān valley	Edited BGN name form
Wādī Jawf fault	do
Wādī Damad drainage basin	do
Red Sea catchment area	do

Letter symbols with BGN names

1. (Y/S) Yemen (Sana)
2. (Y/A) Yemen (Aden)
3. (Y-S/A) Yemen (Sana and Aden)
4. (SA) Saudi Arabia
5. (UAE) United Arab Emirates
6. (Oman) Oman

Geographic features

	Description	Abbreviation	Generic (native) term
1.	dam	dam	
2.	depression	dpr	qāʿ
3.	desert	dsrt	rubʿ
4.	gulf	gulf	
5.	escarpment	escar	
6.	hill	hll	ḥayd, jabal
7.	island	isl	jazīrat
8.	saltmines	mnn	
9.	mountain	mt	ʿalam, jabal
10.	mountains	mts	jibāl
11.	oasis	oas	
12.	independent political entity (republic)	pcli	
13.	plain	pln	jawl, qāʿ
14.	populated area	ppl	
15.	ridge	rdg	ḥayd
16.	region	rgn	
17.	sand area	sand	ramlat
18.	sea	sea	
19.	stream	stm	saylat, wādī, ghayl
20.	strait	strt	bab
21.	valley	val	

BGN (report) name 1/	Feature Description	Coordinates N-Lat	Coordinates E-Long	Sheet number (App.II)
*Ad Dabil (W. ad Dabil) (SA)	stm	15 51	45 54	6
Al ʿAlam al Aswad	mt	15 56	45 46	6
Al Bayḍāʾ	ppl	13 59	45 34	8
Al Ḥaraḍah	ppl	14 05	44 40	8
Al Ḥarf	ppl	16 22	44 06	2
Al Ḥudaydah (Ḥudaydah)	ppl	14 48	42 57	4
Al Luḥayyah	ppl	15 43	42 42	4
*Al Nedja	ppl	15 04	45 17	5
ʿAmrān (ʿUmrān)	ppl	15 41	43 55	4
*ʿAmran valley	val	15 40	43 51	4
Arabian Peninsula (SA)	rgn	25 00	45 00	off
Arabian Sea	sea	18 00	71 00	off
*Arabian Shield (SA)	rgn	25 00	45 00	off
Asir (conv.) (ʿAsīr)(SA)	rgn	19 00	42 00	off
Ash Shaliq (Al Chalek)	ppl	16 06	44 41	2
At Turbah	ppl	13 13	44 07	7
Bab el Mandeb	strt	12 35	43 25	7
Bājil	ppl	15 04	43 17	4
Baraṭ	ppl	16 36	44 15	2
Damt	ppl	14 06	44 43	8
Dhamār	ppl	14 33	44 24	5
Dhī as Sufāl	ppl	13 50	44 07	7
Ghayl Dabāb	stm	13 13	44 18	7
Gulf of Aden	gulf	12 00	48 00	7
Guma	ppl	15 41	42 49	4
Hamman al Lassī (Hayd al Asī)	mt	14 33	44 32	5
Ḥaraḍ	ppl	16 26	43 05	1
Hardha	ppl	15 15	43 15	4
Ḥays (Ḥais)	ppl	13 56	43 29	7
Ibb	ppl	13 58	44 11	7
Ibb ʿAbbās	ppl	15 23	42 47	4
Indian Ocean coast	ocean			off

1/ Translation from glossary or map sources in accordance with the BGN/PCGN (Board on Geographic Names/Permanent Committee of Geographic Names, U.S. and British governmental bodies) system.

BGN (report) name	Feature Description	Coordinates N-Lat	E-Long	Sheet number (App.II)
Jabal adh Dhāmir	mt	15 02	43 23	4
Jabal al Khaṭṭārīn	mt	16 44	43 49	1
Jabal Amā'imah	mt	13 34	44 25	7
Jabal an Nabī Shuʿayb	mt	15 17	43 59	4
Jabal aṣ Ṣafrā'	mt	16 44	43 56	1
Jabal Bārid	mt	13 55	44 11	7
Jabal Buraʿ	mt	14 54	43 29	4
Jabal Ḥaḍur ash Shaykh	mt	15 35	43 50	4
Jabal Khaḍra	mt	13 51	44 12	7
Jabal Manābirah (J. Manabira)	mt	15 29	43 15	4
Jabal Manār	mt	14 02	44 17	7
Jabal Miswar	mt	15 37	43 41	4
Jabal Omrikha	mt	15 09	45 25	5
Jabal Ṣabir	mt	13 30	44 03	7
Jabal Samaʿ	mt	15 10	45 19	5
Jadīdah (Al Jadidah)	ppl	15 03	45 17	5
Jazīrat Jabal Zuqar (Jazīrat Zuqar)	isl	14 00	42 45	off
Jazīrat al Ḥanīsh al Kabīr (Ḥanīsh Kabir)	isl	13 43	42 45	off
Jibāl Dahnah	mts	15 09	43 20	4
Jiblah	ppl	13 55	44 09	7
Kamaran Island (conv.) (Kamarān)	isl	15 21	42 35	off
Kawkabān	ppl	15 30	43 54	4
Khabb (Khabb Oasis)	ppl	16 43	44 54	2
Khamīs al Waʿiẓat	ppl	15 52	43 12	4
Khamr (Khamir)	ppl	15 59	43 58	4
Khashibe Ridge	rdge	16 37	44 51	2
Khāw	ppl	14 18	44 25	5
Khudhrayn (Mt. Khudharain)	hll	16 26	43 09	1
Kitāf	ppl	17 02	44 06	2
Maʿbar	ppl	14 48	44 17	5
Ma'rib	ppl	15 26	45 20	5
*Ma'rib dam	dam	15 27	45 23	5
Māwiyah	ppl	13 35	44 21	7
Mocha (conv.) (Al Mukhā)	ppl	13 19	43 15	7
Nadhīr	mt	16 58	43 16	1
Nakhlah	ppl	13 55	43 34	7
Nuqūb (An Nuqūb) (Y/A)	ppl	14 59	45 48	6
Perim Island (conv.)(Barim)(Y/A)	isl	12 39	42 35	7
Qāʿal Bawn al Kabīr	depr	15 45	44 00	4
Qāʿal Fayd	depr	14 25	44 50	5
Qāʿash Shams	pln	16 09	44 10	5

BGN (report) name	Feature Description	Coordinates N-Lat	E-Long	Sheet number (App.II)
Qāʿ Hays	depr	15 51	44 06	5
Qaʿṭabah	ppl	13 51	44 43	8
Quṭayʿ	ppl	14 54	43 12	4
Rahwah (Rahwat) (Y/A)	ppl	13 59	45 13	8
Ramlat as Sabʿatayn (Y-S/A)	dsrt	15 30	46 10	6
Ramlat Dahn	sand	16 25	45 45	3
Raydah (Rīdah)	ppl	15 50	44 03	5
Red Sea	sea	25 00	35 00	7
Red Sea escarpment	escar			4
Ridāʿ	ppl	14 25	44 50	5
Rubʿ al Khali (conv.) (Ar Rabʿ al Khālī) (Y-S/A,SA,UAE,Oman)	dsrt	21 00	51 00	3
Ṣaʿdah (Sadah)	ppl	16 57	43 46	1
Ṣāfir	mnn	15 39	46 06	6
Sana (conv.) (Ṣanʿā)	ppl	15 21	44 12	5
Salabat as Sayyidah	stm	13 57	44 11	7
Ṣalīf (As Salīf)	ppl	15 18	42 41	4
Saylat Sih (Y-S/A)	stm	13 52	45 07	8
Sūq al Ghinān (Suq al Inan)	ppl	16 43	44 19	2
Taʿizz (Taizz)	ppl	13 34	44 01	7
Tihāmah (At Tihama) (Y-S/A,SA)	pln	22 00	40 00	4
Wādī ʿAbdī	stm	16 57	43 46	1
Wādī Ablah	stm	14 58	45 28	5
Wādī Abrād	stm	15 51	46 05	5
Wādī Adhanah	stm	15 24	45 16	5
Wādī al Adīr	stm	13 12	44 18	7
Wādī al ʿAqīq	stm	17 03	44 27	2
Wādī Agnām	stm	17 00	43 47	1
Wādī Ajlub	stm	14 06	44 40	8
Wādī ʿAnnah	stm	14 04	43 44	7
Wādī Amid	stm	13 42	44 11	7
Wādī Amlaḥ	stm	17 10	44 33	2
Wādī Amwaḥ (Y/S, SA)	stm	17 00	45 40	2
Wādī Aṭṭāf (Ghayl Hirran)	stm	16 02	44 12	2
Wādī ʿAyyan	stm	15 28	42 46	4
Wādī Aẓlah	stm	16 57	44 19	2
Wādī Banā (Y-S/A)	stm	13 03	45 24	8
Wadi Banī Nāshir	stm	15 52	43 13	4
Wādī Bawḥal	stm	16 05	43 03	1
Wādī Bayḥan	stm	15 11	45 51	6
Wādī Birkah	stm	16 25	44 06	2
Wādī Dabbah (W. Shamera Dabbah)	stm	13 31	44 25	7
Wadi Dahr	stm	13 31	44 15	7
Wadi Ḍahr	stm	15 27	44 08	5

BGN (report) name	Feature Description	Coordinates N-Lat	E-Long	Sheet number (App.II)
Wādī Ḍamad (SA)	stm	16 59	42 33	1
Wādī Ḍammar (W. Dammer)	stm	16 53	43 48	1
Wadi Difāʻah (W. Ad Dafa)	stm	17 47	42 54	1
Wādī Dhī as Sufal (W. Zuba)	stm	13 46	44 09	7
Wadi Dhubāwah	stm	15 52	43 34	4
Wādī Fawān	stm	13 05	44 05	7
Wadi al Furḍah	stm	15 51	44 45	5
Wadi al Fawwahāh	stm	13 55	43 12	7
Wādī al Ghayl	stm	13 17	43 15	7
Wādī al Ghayl	stm	14 35	45 39	6
Wādī Ḥabl	stm	16 10	42 52	1
Wādī Ḥaḍramawt (Y/A)	stm	16 00	48 53	off
Wādī Ḥalḥalan	stm	15 55	45 11	5
Wadi Ḥammān (W. Anman)	stm	14 13	43 53	7
Wādī Ḥamrā' (Y-S/A)	stm	13 59	45 09	8
Wādī Ḥanabah	stm	17 24	43 18	1
Wādī Ḥarīb (Y-S/A)	stm	15 30	45 58	6
Wādī Ḥarrīnah (W. Harrine)	stm	16 16	44 07	2
Wādī Ḥaraḍ (Y-S/A)	stm	16 25	42 46	1
Wādī Ḥaṭab	stm	15 26	43 02	4
Wādī Ḥaṭib	stm	13 50	45 06	8
Wādī Ḥaydān	stm	15 37	43 58	4
Wādī Ḥayrān	stm	16 16	42 53	1
Wādī Ḥijlah	stm	1532	43 38	4
Wādī ʻIjal ʻAlī	stm	15 33	43 41	4
Wādī ʻIlāf	stm	16 57	43 44	1
Wādī ʻImārah (W. Imara)	stm	17 12	44 37	2
Wādī al Jufrah	stm	15 53	45 04	5
Wādī Jawf	stm	15 50	45 30	5
Wādī Jumhūrī (W. Gumhuri)(Y/A)	stm	14 35	46 07	6
Wādī Jirādhah	stm	15 00	45 32	5
Wādī Jīzān (W. Qīzān) (SA)	stm	16 57	42 33	1
Wādī Kaleyba	stm	13 20	43 48	7
Wādī Khabb (W. Khubb) (Y/A,SA)	stm	17 00	45 30	2
Wādī Khadir	stm	13 30	44 16	7
Wādī Khadwān	stm	17 17	44 10	2
Wādī Khalīfayn	stm	16 27	45 10	2
Wādī al Khāniq (W. Manqai)	stm	15 17	45 18	5
Wādī al Khārid	stm	16 07	44 44	2
Wādī Khayrah	stm	16 25	44 05	2
Wādī Khulab (SA)	stm	16 38	42 44	1
Wādī Lāʻah	stm	15 37	43 19	4
Wādī Laylān (SA)	stm	14 05	45 55	8
Wādī Liyyah (Y/S, SA)	stm	16 34	42 55	1
Wādī Maʻbar	stm	17 05	43 15	1
Wādī Madhāb	stm	16 27	44 20	2
Wādī Maksab	stm	13 18	43 34	7
Wādī Mansib	stm	15 37	43 57	4

BGN (report) name	Feature Description	Coordinates N-Lat	E-Long	Sheet number (App.II)
Wādī Markhah (Y-S/A)	stm	14 59	46 36	6
Wādī Mawr	stm	15 41	42 42	4
Wadi Maydī (?)	stm	16 21	42 49	1
Wādī Najrān (SA)	stm	17 33	45 00	2
Wādī Nakhlān	stm	13 47	44 10	7
Wādī Qaʿif (W. Qu ayf)	stm	17 00	44 56	2
Wadi al Qawl	stm	14 14	45 55	8
Wādī Qumāmah	stm	15 39	43 52	4
Wādī al Qūr (W. al Our)	stm	16 00	43 06	1
Wādī Quwah (Y-S/A)	stm	14 34	46 06	6
Wādī Raghwān (W. al Mukhaynia)	stm	15 46	45 06	5
Wādī Rasyān	stm	13 35	43 17	7
Wādī Rimaʿ	stm	14 15	43 05	4
Wādī Rummān (W. Roman)	stm	15 32	43 39	4
Wādī Salab	stm	15 39	43 52	4
Wādī Samʿ	stm	15 33	43 28	4
Wādī Saram	stm	13 24	44 12	7
Wādī Shamera (W. Shamera Dabbah)	stm	13 32	44 23	7
Wādī Sharas	stm	15 51	43 40	4
Wādī Shebe	stm	15 22	42 58	4
Wādī Shuqbān	stm	16 32	45 15	2
Wādī Silbah (W. Silba)	stm	16 58	45 01	2
Wādī Sihām	stm	14 42	42 58	4
Wādī as Sirr	stm	15 34	44 17	5
Wādī Subr	stm	17 02	43 40	1
Wādī as Sudd (W. Saba)	stm	15 26	45 21	5
Wādī Suḥūl	stm	14 13	43 58	7
Wādī Surdūd	stm	15 10	42 52	4
Wādī Suwayhirah (W. Suwarhira)	stm	13 49	43 15	7
Wādī Taʿashshar (Y/S, SA)	stm	16 31	42 44	1
Wādī Tabāb	stm	15 27	43 02	4
Wādī Tānif	stm	13 45	44 05	7
Wādī Tisʿān (Y-S/A)	stm	13 36	44 32	7
Wādī Tuban (Y-S/A)	stm	13 07	44 51	7
Wādī Thuʿbān (W. Thaʿbān) (SA)	stm	17 25	43 45	1
Wādī ʿUkayyān	stm	13 03	44 05	7
Wādī ʿUlaysī	stm	15 24	42 48	4
Wādī Warazān (Y-S/A)	stm	13 26	44 21	7
Wādī Warū (W. Husayb)	stm	15 44	43 25	4
Wādī Yahir (W. Yislam)	stm	14 15	44 53	5
Wādī Zabīd	stm	14 07	43 06	7
Wādī Zaydan	stm	14 16	44 53	5
Wāsiṭah	ppl	14 49	44 17	5

BGN (report) name	Feature Description	Coordinates N-Lat	Coordinates E-Long	Sheet number (App.II)
Yakhtul	ppl	13 27	43 16	7
Yarīm	ppl	14 18	44 23	5
Yemen (Sana)	pcli	15 00	44 00	8
Yemen Arab Republic (conv.)				
Al Yaman (Arabic; short form)				
Al Jumhūrīyah al Arabīyah al Yamanīyah (Arabic; long form)				
Yemen (Aden)	pcli	14 00	46 00	8
Peoples Democratic Republic of Yemen (conv.)				
Al-Yaman (Arabic; short form)				
Jumhūrīyat al Yaman ad Dīmuqrāṭīyah ash Shaʿbīyah (Arabic; long form)				
Zabīd	ppl	14 12	43 19	7

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